Engineering Laboratories Division
Hydraulic Laboratory Branch

UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

HYDRAULIC MODEL STUDIES OF THE MORNING-GLORY SPILLWAY FOR HUNGRY HORSE DAM

HUNGRY HORSE DAM PROJECT

Hydraulic Laboratory Report No. Hyd-355

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OFFICE OF THE ASSISTANT COMMISSIONER AND CHIEF ENGINEER
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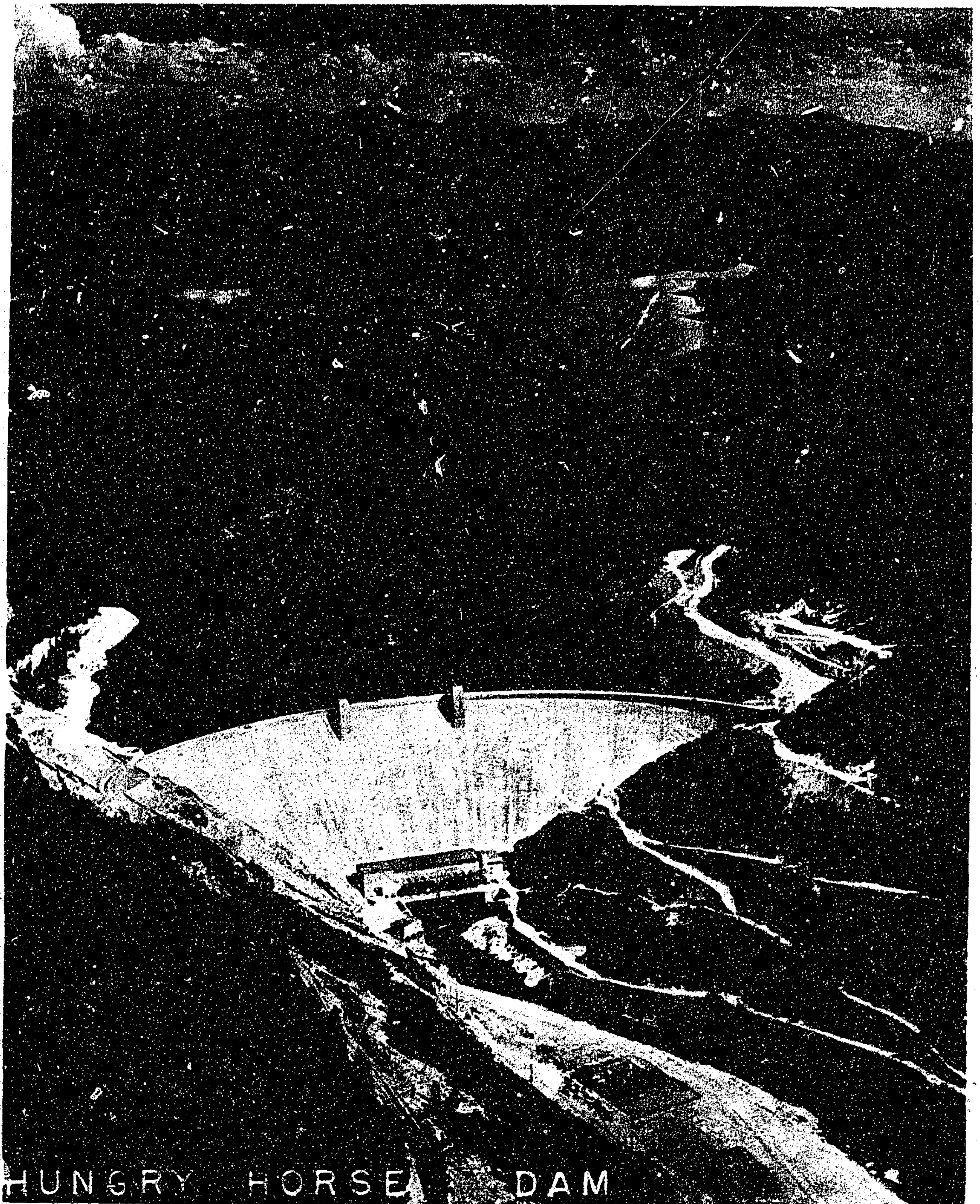
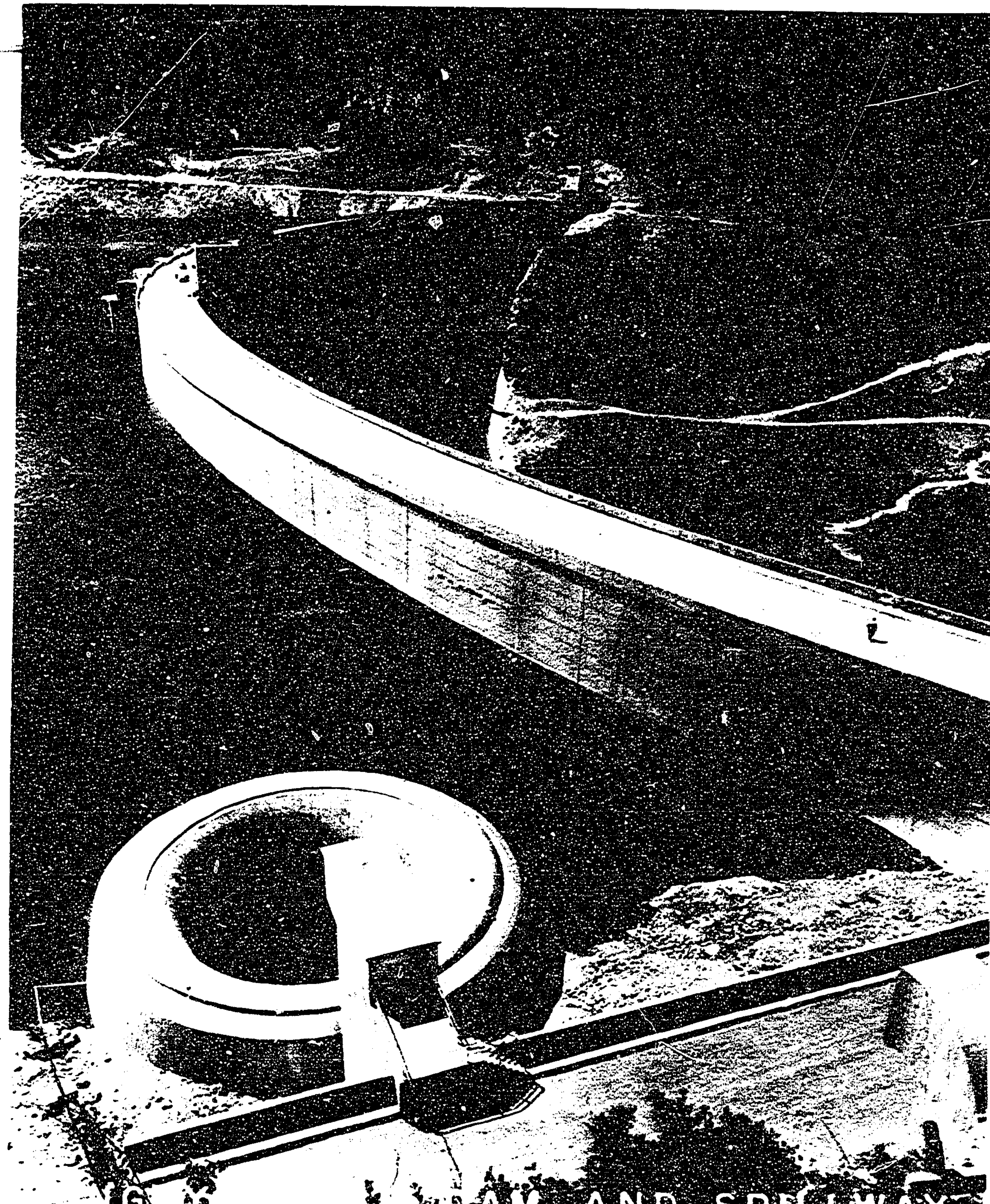

HUNGRY HORSE DAM


DAM AND SPILLWAY


MORNING GLORY SPILLWAY

FOREWARD

Hydraulic model studies of the Hungry Horse Dam Spillway, a part of the Hungry Horse Project, were conducted in the Hydraulic Laboratory of the Bureau of Reclamation at Denver, Colorado, during the period February 1948 to July 1950. A few tests were made as late as March 1951, however.

The final plans evolved from this study were developed through the cooperation of the staffs of the Chief Designing Engineer's office, the Spillway and Outlets Section of the Dams Division, the Large Gates and Valves Section of the Mechanical Division, the Steel Pipes and Penstocks Section of the Mechanical Division, the switchyard section of the Electrical Division, the Structural and Architectural Division, the Hydraulic Machinery Division, the Construction Engineer's office, the Hydrology Division, and the Hydraulic Laboratory.

During the course of the model studies W. H. Nalder, Chief Designing Engineer; L. G. Puls and O. L. Rice, both representatives of the Chief Designing Engineer; D. C. McConaughy who was responsible for the major portion of the design and L. M. Stimson, both of the Spillway and Outlets Section; W. G. Weber, B. H. Staats, and J. W. Adolphson, all of the Large Gates and Valves Section; C. O. Selander of the Steel Pipes and Penstocks Section; D. M. Robinson, R. S. Saliman, and C. R. Hughes all of the Structural and Architectural Division; D. C. Millard and J. F. Hayden both of the Switchyard Section of the Electrical Division; E. H. Johnson of the Hydraulic Machinery Division; K. B. Keener, Head of Dams Division; J. K. Richardson, Head of Mechanical Division; S. Judd, Head of Structural and Architectural Division; Clyde Spencer, Construction Engineer; and others visited the laboratory to observe model tests and to discuss the test results with J. E. Warnock, H. M. Martin, J. N. Bradley, A. J. Peterka, W. E. Wagner, and G. L. Beichley of the Hydraulic Laboratory.

These studies were conducted by G. L. Beichley with the aid of Yin Feng, A. S. Reinhart, W. B. McBirney, R. E. Selleck, F. D. Witaschek, G. C. McKinney, L. A. Browning, K. J. Von Farrel, and others under the direct supervision of W. E. Wagner, A. J. Peterka, and J. N. Bradley.

CONTENTS

CONTENTS--Continued

CONTENTS--Continued

CONTENTS--Continued

CONTENTS--Continued

CONTENTS--Continued

UNITED STATES
DEPARTMENT OF THE INTERIOR
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Office of Assistant Commissioner
and Chief Engineer
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Laboratory Report No. Hyd-355
Hydraulic Laboratory
Compiled by: G. L. Beichley
Checked and
reviewed by: A. J. Peterka
J. N. Bradley

Subject: Hydraulic model studies of the morning-glory spillway for Hungry Horse Dam--Hungry Horse Project

SUMMARY

Hydraulic model studies of the morning-glory spillway for Hungry Horse Dam (Figures 1 through 7) were made on a 1:36 scale model (Figures 8 through 17) and a 1:40.94 circular weir model (Figures 18, 19, and 20) for the purpose of developing the hydraulic design. The morning-glory spillway, which was equipped with an adjustable ring gate crest structure and discharged into a tapered and sloping tunnel, presented unusual and difficult hydraulic problems. Although from a hydraulic point of view it was recommended that an open channel entrance structure be used at the upper end of the tunnel, structural limitations made the use of the morning-glory entrance necessary. The tests were, therefore, concerned primarily with developing a satisfactory morning-glory crest structure and tunnel.

The scope of the investigation included: the study of the flow approaching the spillway; the testing of the preliminary morning-glory with and without radial entrance piers, and with and without vents in the upper bend; the testing of three other morning-glory spillways including the recommended design which was developed in the laboratory by use of a separate circular weir model; the testing of the recommended morning-glory with several proposed venting systems including the recommended system; the study of the flow through the tunnel; the testing of the preliminary lower bend and two other proposed lower bends, including the recommended design; the study of flow conditions in the downstream area including a study of the spillway jet, erosion, and flow characteristics in the river channel with various combinations of spillway, outlet, and powerhouse discharges.

In conducting the investigation, two separate models were constructed and tested; approximately 200 tests were performed; approximately 200 piezometers were used; approximately 240 pictures were taken; and approximately 1,200 feet of 16-mm movie film were exposed. Only the more pertinent of this data is presented in this report.

As a result of the model studies, severe subatmospheric pressures were eliminated in the preliminary morning-glory (Figures 27 and 44) and (Tables 4 and 5) and in the spillway tunnel (Figure 28) and (Tables 4 and 5). The subatmospheric pressure conditions was corrected by developing a better crest profile for the morning-glory (Figure 42) and by developing an efficient venting system (Figures 6 and 7). Flow conditions downstream from the lower bend were improved (Figure 35) by increasing the radius of the lower bend from 55 to 120 feet (Figure 34). These improved flow conditions helped to reduce subatmospheric pressures in the tunnel by improving the ventilation. Flow conditions in the tunnel were also improved by developing a guide vane for the upper bend together with a pier located on the spillway crest (compare Figures 46, 47, and 48 with Figures 55, 56, and 57). However, this arrangement was rejected by the designers because of difficulties in constructing the vane in the prototype. The spillway was calibrated to check the capacity of the structure and to use later in operating the prototype structure (Figure 51). Unbalanced pressures on the ring gate were determined for use in designing the ring gate (Figures 49 and 50). In the river channel area, it was found that the spillway and outlet jets lowered the water surface in the powerhouse tailrace to such an extent that a small dam across the channel was necessary in order to be sure that the minimum allowable tail-water elevation would be maintained for operating the turbines (Figure 61). The model studies showed that relocation of the transmission lines from the powerhouse was necessary because they were originally too close to the spillway and outlet jets (Figure 62). Operation of the model also showed the necessity for providing riprap or other protection to the riverbank near the switchyard, the access road to the switchyard, and the conduit containing the switchyard control cables.

INTRODUCTION

Hungry Horse Dam, part of the Hungry Horse Project, is located on the south fork of the Flathead River in northwestern Montana between Glacier National Park and Kalispell, Montana, as shown in Figures 1A and B. The dam shown in Figure 2 is a concrete arch approximately 2,100 feet long at the crest and has a maximum height of about 520 feet above the foundation.

The spillway, located in the right abutment as shown in Figure 3, is a concrete-lined tunnel with a morning-glory type entrance. The morning-glory is equipped with a ring-gate controlled crest as shown in Figure 4. The morning-glory concrete structure as preliminarily designed is shown in Figure 5, but as a result of this study, it was redesigned as shown in Figures 6a, 6b, and 6c. The diameter of the crest line of the ring gate is 64 feet. The gate can be elevated a maximum of 12 feet by means of the control mechanism housed in a pier located on the shore side of the morning-glory.

With the ring gate seated in the down position the crest line is at elevation 3548, 16.9 feet below the maximum reservoir elevation, and the spillway is designed to discharge a maximum of approximately 50,000 second-feet, or approximately 250 second-feet per lineal foot of crest length. The throat, or base of the converging section of the morning-glory, is 37 feet in diameter at elevation 3520, 28 feet below the crest line of the ring gate when seated.

From the throat the tunnel bends 40° to an incline of 50° with the horizontal and tapers from a diameter of 37 feet at the throat to 34.79 feet at the upstream end of the incline. The incline has a total vertical drop of 341.3 feet and tapers to 24.5-foot diameter at the downstream end. A vertical bend of 49°53'28" connects the inclined tunnel to the nearly horizontal tunnel which continues to the outlet portal on a slope of 0.0019. The tunnel is 24.5 feet in diameter throughout the lower bend and for a distance of 219.25 feet downstream, then is transformed through a 166-foot-long transition section to a 31-foot-diameter horseshoe tunnel. The horseshoe section of tunnel continues 113.5 feet to the outlet portal. Thus, from the spillway crest to the invert of the tunnel at the outlet portal, the spillway discharge drops a vertical distance of 475.5 feet in a horizontal distance of 1,402.09 feet, measured from the center of the morning-glory to the outlet portal. At the outlet portal a deflector or flip bucket, shown in Figure 3, deflects the flow from the spillway tunnel to an area in the river channel some distance downstream.

The undernappe of the flow through the morning-glory is ventilated by nine 8-inch standard pipes flattened to 3-inch inside width at the outlet end and spaced on 30° centers in the concrete crest structure, as shown in Figures 6a and 6c. The 8-inch air vents are manifolded in a more or less triangular-shaped air chamber which encircles the interior of the structure at approximate elevation 3529. Air is supplied to this circular chamber through a 2-foot 6-inch square duct extending vertically downward to a 6-foot-square air inlet tunnel which opens to the atmosphere in the right abutment, as shown in Figure 7. The air inlet tunnel also opens into the crown of the spillway tunnel in the upper bend just below the throat at center line elevation 3514, for the purpose of supplying air to the spillway tunnel. This venting system was designed by the Spillway and Outlets Section No. 1 based on the model studies.

The power plant at Hungry Horse Dam shown in Figure 2 is located at the toe of the dam and accommodates four main generating units. Each unit discharges a maximum of 2,800 second-feet.

The outlet works located on the right bank of the river channel a short distance upstream from the spillway outlet portal shown in Figure 2 consists of three 96-inch-diameter outlet conduits that discharge a maximum of 5,000 second-feet each into the river channel from the valve house. Discharges are controlled by 96-inch hollow-jet valves located on the ends of the conduits. A stilling basin was not provided because the river channel was believed to be nearly solid rock and, therefore, capable of withstanding the impact of the jets without causing much erosion.

THE MODELS

Two models were used in the investigation. One was a 1:36 scale model reproduction of the spillway which included the powerhouse area and the outlet works valves as well as the area surrounding the spillway entrance and the river channel downstream, as shown in Figures 8 to 17, inclusive. The other model was a 1:40.94 scale circular weir shown in Figures 18, 19, and 20. The two models were constructed and tested in the Bureau of Reclamation Hydraulic Laboratory at the Denver Federal Center.

The Spillway Model

The spillway model consisted of three main parts: (1) the reservoir area, consisting of a portion of the upstream face of the dam, the morning-glory structure, and the topography surrounding the morning-glory; (2) the tunnel; and (3) the downstream area, consisting of the outlet portal of the spillway, the valves of the outlet works, and a length of river channel extending from the powerhouse to approximately 1,400 feet downstream from the spillway portal.

The Reservoir Area

The reservoir area was contained in a head box which allowed reproduction of the reservoir for 430 feet upstream from face of dam and for 270 feet to the left of the morning-glory. Topography in the reservoir area was molded of concrete mortar placed on metal lath as shown in Figure 12. Two sections of the topography surrounding the morning-glory and the control pier were made as separate removal pieces in order that repairs and model alterations to the morning-glory could easily be made. The surface was given a rough finish to simulate the natural topography of the prototype.

The shape of the morning-glory crest structure in the reservoir was revised three times during the course of the investigation. For each revision the method of model construction was varied somewhat.

Preliminary morning-glory crest structure, ring gate, and vents. The preliminary prototype crest structure shown in Figure 5 and the ring gate shown in Figure 4 were designed for model construction as shown in Figures 13 and 14. The morning-glory crest structure was made of transparent plastic, the ring gate of brass, and the gate control pier of sheet metal. The model ring gate was constructed so that it could be raised and lowered by means of a gear arrangement with a removable handwheel placed on the end of a shaft extending upward through the control pier. In the prototype, the air shaft from the atmosphere to the air duct encircling the interior of the crest was located in the control pier, but in the model it was constructed as a separate air supply duct. The fifty-two 8-inch standard pipe air vents in the prototype shown in Figure 5 were approximated in the model by orifice openings cut to scale at the proper location in the transparent plastic air chamber.

Second morning-glory crest structure, ring gate, and vents. The morning-glory model of the second crest structure tested was molded of concrete placed on metal lath as shown in Figure 15. A revolving template was used to form the profile of the morning-glory. This method of construction proved to be very satisfactory and economical. The ring gate for this design was a sharp crested circular weir. It was also molded of concrete mortar, and was made as a separate piece that could be set in place and removed easily. There was no ring-gate mechanism in the modified model to move the gate up and down; instead three interchangeable ring gates were made, each of a different height, which provided two elevations of the ring gate in addition to the seated position. Air vents were not used in this crest structure but were provided in the periphery of the upper bend immediately downstream from the morning-glory.

Third morning-glory crest structure, ring gate, and vents. For the third morning-glory crest structure, parts of the preliminary morning-glory model were reused without alteration. The ring gate, control pier, and the plexiglass portion of the crest outside of the ring gate were reused. The morning-glory crest profile inside of the ring gate was molded in concrete similar to the method used in construction of the second crest structure. No vents under the gate lip were used in this structure but other venting schemes were tested. They are described in the investigation.

Recommended morning-glory crest structure, ring gate, and vents. The recommended prototype crest structure and ring gate shown in Figures 6a, 6b, 6c, 7, and 4 as constructed for the model are shown in Figure 16. The ring gate, control pier, and the outer plastic portion of the crest structure were all reused from the model of the preliminary design, with but one alteration to the ring gate. The recommended crest portion of the ring gate was molded of concrete mortar placed over metal lath. The metal lath was fastened to a circular sheet metal form that was soldered in place on the brass ring-gate structure. The portion of the crest structure inside the ring gate was molded in concrete by the same method used for molding the second and third crest structures.

The recommended venting system in the prototype crest structure and upper bend shown in Figures 6a, 6c, and 7 as constructed in the model is shown in Figure 16. The 6-foot-square concrete air inlet tunnel was made of transparent plastic in the model. It was made to scale as far as size and length were concerned, but the five vertical bends in the prototype were replaced by one right-angle vertical bend in the model because interference of head box and model topography made it almost impossible to do otherwise. It was not considered necessary that the vertical bends be simulated. The air chamber encircling the interior of the crest was constructed of sheet metal and was not to scale in the model. The nine vents from the air chamber to the undernappe, however, were constructed to scale and placed in their proper location. The 2-foot 6-inch square vertical air duct, which connected the circular air chamber to the air inlet tunnel, was constructed of sheet metal and built to scale in the model.

Spillway Tunnel

The preliminary spillway tunnel including the recommended upper and lower bends was constructed of transparent plastic in the model as shown in Figures 8 and 9. The model tunnel was geometrically similar to the prototype except for its length. The model tunnel was shortened to compensate for the proportionately greater friction loss in the model. The computation of the tunnel length reduction is described later in the description of the preliminary morning-glory spillway on page 13.

The Downstream Area

The downstream area was contained in a tail box which allowed reproduction of the river channel from the powerhouse to 770 feet downstream from the spillway deflector as shown in Figures 8 and 9a. The tail box was later extended as shown in Figures 10 and 11 to reproduce approximately 1,400 feet of river channel downstream from the spillway portal.

The spillway deflector at the outlet portal was molded of concrete mortar placed on metal lath. Sheet metal templates in the concrete were used as guides for forming the deflector to exact shape. Topography of the river channel downstream from the dam was molded of concrete between elevations 3080 and 3110 using mortar placed on metal lath similar to the method used in the reservoir area. The river bed below elevation 3080 was first formed in gravel to form an erodible bed in which the erosion could be evaluated by model test. A sample of the gravel used in the erodible bed was analyzed for size and found to be as shown by the following sieve analysis:

Retained on 3/4-inch screen	6 percent
Retained on 3/8-inch screen	66 percent
Retained on No. 4 screen	25 percent
Retained on pan	3 percent

At the completion of the erosion tests, the erodible bed was stabilized by surfacing the river channel with a 3/4-inch layer of concrete placed to grade directly over the gravel. Other additions in the river channel area were made during the course of the investigation and are shown in Figures 10 and 11. These additions included the extension of the downstream river channel, installation of the outlet works hollow-jet valves, installation of facilities for simulating the power plant and outlet works flows, and installations of the switchyard and transmission lines leading from the power plant.

Water Supply

Water was supplied to the reservoir by portable 6- and 8-inch pumps, pumping in parallel through an 8-inch line. The discharge was metered by an 8-inch orifice-venturi meter placed in the supply line. Flow-straightening vanes were installed in the supply line upstream from the meter to closely duplicate the arrangement under which the meter was calibrated.

Water was supplied to the power plant and outlet works by a separate portable 8-inch pump through an 8-inch line as shown in Figure 10. The combined discharge to the power plant and three outlet valves was metered by an 8-inch orifice-venturi meter placed in the supply line. That portion going to the outlet works was measured as follows: With one outlet valve open and the power plant closed, the piezometer located one diameter upstream from the open valve was set to the computed pressure head for the maximum discharge of one valve by adjusting the valve opening. The other two hollow-jet valves were then opened to the same number of turns of the operating handles as the first, thereby insuring equal discharges through each of the three outlet valves. Then, the main valve in the outlet works supply line and the one in the power plant supply line were regulated in such a manner that the total discharge flowing, as measured by the orifice-venturi meter, was the combined discharge of the power plant and the three outlets, and that the pressure head one diameter upstream from the hollow-jet valve remained as originally set. This method assured the correct division of the maximum discharge through the power plant and each of the outlet valves.

Water Surface Gages

The reservoir and tail-water elevations were measured by a hook-gage-in-well and staff gages, respectively, placed as shown in Figures 8 and 10. The tail-water elevation was controlled by a gate at the extreme downstream end of the model. Tail-water settings were determined from the tail-water curve in Figure 3, which was submitted to the laboratory for use in the model tests.

Piezometers

Piezometers were used to measure pressures throughout the spillway structure. The piezometer locations in the preliminary morning-glory crest structure and ring gate are shown in Figure 13. The piezometer locations in the preliminary spillway tunnel and two model revisions of the spillway tunnel are shown in Figure 8. Piezometer locations in the recommended morning-glory crest structure, ring gate, air vent system, and spillway tunnel are shown in Figure 17. Piezometer pressures in the crown of the tunnel were measured with a portable U-tube water manometer, while all others were measured with permanent single-leg water manometers.

The Circular Weir Model

The circular weir model was used to determine the crest profile of the recommended crest structure by measuring the shape of the undernappe profile over the weir. The general arrangement of the model is shown in Figure 18. Further details are shown in Figures 19 and 20.

The Weir

The weir shown in Figures 18 and 19 was fabricated from a 20-inch length of seamless steel pipe 20 inches in outside diameter with a 1/2-inch-thick wall. A steel flange, for bolting the weir to the floor of the head box was welded to one end of the pipe. The outside surface of the other end of the cylinder was machined to form a true circle, 1.6597 feet in diameter which represented the 68-foot diameter of the spillway ring gate. The scale of the model was therefore computed to be 1 to 40.94. A 45° bevel was then machined on the inner face until a knife edge was formed by the intersection of the 45° bevel and the outer machined surface.

The Reservoir

Topography was not used in the reservoir. The reservoir was merely a pool of water surrounding the circular weir which provided uniform radial flow approaching the weir.

The reservoir was contained in the head box shown in Figures 18 and 19. The box was 12 feet square with sidewalls 4 feet high (outside dimensions) and was elevated to a bottom height of 5 feet above the laboratory floor. The primary horizontal supports for the head box consisted of 6- by 1-7/8-inch steel channels welded together to form a grid, 4 feet on centers, under the head box. Each corner of this grid was supported by a 3-1/2-inch outside diameter steel pipe (16 in all) placed on end on the laboratory floor. To support the circular weir, a 1/4-inch steel plate approximately 4 feet square, was welded in place over the center grid of channels. Secondary horizontal supports, consisting of 2- by 2-inch steel angles, were welded to two sides of the remaining grids thus forming a 2- by 4-foot grid work under the remainder of the head box.

Three-fourths-inch plywood was bolted to the steel framework to form the floor of the head box. The sidewalls of the head box consisted of 2- by 4-inch fir studding, on 12-inch centers, faced on the inside with 3/4-inch sheathing. The floor and sidewalls were then lined with 28-gage galvanized sheet metal. The circular weir was bolted to the plywood and steel plate in the center of the head box, using a 1/8-inch rubber gasket to make a watertight joint. The construction of the box and weir was thus sufficiently rigid to maintain the weir in a level position when the head box was full of water.

Water was supplied to the head box through two 8-inch inlets which terminated in the floor at diagonal corners of the box. Several precautions were taken to assure that the water approached the weir radially and uniformly in order to simulate the ideal approach condition. A 6-inch-thick baffle, containing 3/4- to 1-inch gravel, was placed approximately 1 foot from the sidewalls of the head box (Figure 19). Two steel gratings were placed over each inlet to reduce the boil and distribute the inflowing water between the sidewalls of the head box and the gravel baffle. To further quiet the flow before passing over the weir, a perforated cylinder was placed between the gravel baffle and the weir. The perforated cylinder, 6-1/2 feet in diameter and 4 feet high, was made from a 12-gage steel plate punched with one hundred 13/16-inch diameter holes per square foot.

Discharge Measurements

The discharge over the circular weir was measured by either a 4-, 6-, 8-, or 12-inch commercial venturi meter, depending upon the discharge required for the particular test. The differential pressure in the venturi meters, calibrated in place, was indicated by means of a mercury manometer. The mercury manometer and venturi meters are part of the permanent laboratory test equipment and no special calibration of the meters was made for these tests. However, all the laboratory venturi meters, including the ones used in these experiments, were accurately calibrated by means of a volumetric tank during the summer of 1951. The latter calibration, which differs very little from previous ones, was used in computing the discharge over the weir.

Water Surface Gages

Head gage. The head on the test weir was measured by a hook gage mounted in a stilling well located at the corner of the head box as shown in Figure 18. A 3/16-inch inside-diameter rubber tube connected the stilling well to a 1/2-inch copper pipe soldered to the sheet metal lining of the floor of the head box at a point 22 inches from the sharp crest of the circular weir.

Undernappe gage. To determine the shape of the undernappe surface, the profile first was outlined by means of 13 wire probes extending through the wall of the weir and spaced at intervals below the crest of the weir. Several of the probes are shown in Figure 19b. The end of each probe was positioned along the nappe by screwing the probe, using handles located beneath the head box floor toward the sheet of water until contact was made with the lower nappe surface. Contact of the probe with the nappe was indicated by a 6-volt bulb which lighted when the end of the probe barely touched the lower nappe surface. Figure 20 shows the probe adjustment screws and the electronic contact indicator.

The coordinates of the points of the probes outlining the undernappe profile were measured after each test with a specially designed point gage shown in Figure 19b. The gage was made entirely of brass and consisted of a horizontal beam placed on the crest of the test weir and a vertical bar mounted in a carriage that could be slid along the horizontal beam. The lower end of the vertical bar was fitted with a point for positioning the gage to the end of the wire probe. The point of the gage was positioned over the probe by moving the carriage horizontally along the beam and lowering the vertical bar until the point contacted the probe. Both horizontal and vertical bars were graduated to 0.01 foot, with verniers reading to 0.001 foot. The zero of the gage was determined by positioning the point gage at the crest of the weir.

Means of Reducing the Pressure Under the Nappe

To study the effect of subatmospheric pressures under the nappe, a sheet metal cylinder, 35 inches in diameter, 3 feet long, and flanged at one end, was bolted to the underside of the head box concentric with the circular weir as shown in Figure 20b. The cylinder contained a large plastic window for viewing the jet falling from the circular weir above. The lower end of the cylinder was approximately 9 inches from the floor of the tail box. By means of a tailgate, the water surface in the tail box could be raised to submerge the end of the cylinder, thus sealing the air chamber between the falling jet and the cylinder walls. The jet, in falling, pumped air from the chamber and reduced the pressure in the space beneath the nappe. Two vents shown in Figure 20b, each 3 inches in diameter and equipped with gate valves, were placed in the wall of the cylinder. By controlling the amount of air entering the chamber, a fairly stable pressure could be maintained under the nappe. For the lower pressures and discharges, it was found necessary to connect a vacuum line to the chamber to secure the desired pressure.

The pressure in the chamber was measured by a differential water U-tube manometer as shown in Figure 20b. The legs of the manometer were tilted at 45° to permit reading of the differential pressure at 0.001 foot.

THE INVESTIGATION

Purpose and Scope

The purpose of the over-all investigation was to develop the hydraulic design of the morning-glory spillway. In developing the design it was necessary to study the characteristics of the flow as it approached the spillway, as it entered the morning-glory, as it flowed through the morning-glory and through the tunnel, and as it entered the river channel downstream from the dam.

The preliminary morning-glory was tested with and without radial entrance piers on the spillway face and with and without vents in the upper bend. Three other morning-glory shapes were tested during the development including the recommended design. The circular weir model was used to develop the crest shape of the recommended morning-glory design. The recommended morning-glory was then tested with several proposed venting systems including the recommended venting system. In developing the tunnel design the model was tested using the preliminary lower bend and two other lower bends, one of the latter being the recommended design.

The investigation began with the study of the flow approaching and entering the morning-glory, then centered on the morning-glory, spillway tunnel, and venting system, and finally on the flow entering the river channel. In addition to the data shown and reported here, approximately 1,250 feet of 16-mm film were exposed showing the operation of the preliminary spillway and final recommended spillway for discharges of 5,000, 35,000, and 50,000 second-feet. Approximately 150 feet of 16-mm film were used to record the operation of the circular weir model.

Spillway Approach

The spillway approach area is shown in Figures 3, 8, and 12b. Flow approaching and entering the morning-glory is shown in Figure 9b, and in Figure 21 for discharges of 10,000, 30,000, and 53,000 second-feet with the ring gate seated. At the beginning of the investigation 53,000 second-feet was considered to be the maximum design discharge.

Since the source of all flow entering the spillway was from the left of the morning-glory, the flow lines appeared to veer to the right and left of the morning-glory to meet at the control pier to form a fin and a concentration of water as shown in Figure 22 for discharges of 10,000, 30,000, and 53,000 second-feet with the gate seated. This type of flow pattern will henceforth be referred to as tangential flow in this report. If the morning-glory were located in the reservoir several hundred feet from shore, it would have drawn water more equally from all sides in making the flow pattern radial. Since it was not practical to locate the morning-glory far from shore, it was felt that removing the pier and adjacent topography might be sufficient to cause the flow pattern to be more nearly radial thereby eliminating the fin of water. A test with this arrangement showed the flow pattern to be little different than before. The fin was still present but had shifted slightly clockwise from its previous location. The fin occurred at the point where the flow currents from the left met the flow currents from the right. The pier in place merely shifted the point of convergence slightly counterclockwise from the natural meeting point.

The disadvantage of the tangential flow pattern and the accompanying fin is that the bulk of the flow entered the morning-glory at the control pier, approximately 64° to the right of the tunnel center line, causing the flow through the tunnel to zigzag from one side to the other as shown in Figures 23 and 24. Part of the flow spiraled completely over the crown of the tunnel for some discharges and gate positions. Flow through the tunnel might have been straighter had it been possible to locate the pier on the tunnel center line. Attempts to straighten the flow are discussed in Step 18 of the morning-glory crest and spillway tunnel section of this report.

For large spillway flows small eddies occurred upstream and to the left of the control pier as can be seen in Figure 21(c). They were caused, apparently, by the shape of the excavated area. Since the eddies were small and occurred only for the exceedingly high discharges, it did not seem advisable to recommend additional excavation of the rock topography in that area.

The flow pattern in the spillway approach was observed for a range of discharges with the ring gate elevated and with the water surface at the maximum reservoir elevation. Problems similar to those just described were encountered.

Morning-glory Crest and Spillway Tunnel

Preliminary Morning-glory Spillway

Description. The preliminary morning-glory shown in Figures 5 and 25a was constructed in the model as shown in Figures 13 and 14. The preliminary tunnel shown in Figure 2 was constructed in the model as shown in Figures 8 and 9.

For the purpose of studying the erosion and the characteristics of the flow in the channel downstream from the spillway, the velocity of the flow leaving the model tunnel must approximate, to scale, the prototype velocity. Therefore, it was necessary to correct for the proportionally higher friction losses of the model by either increasing the slope of the inclined model tunnel or by shortening the tunnel, or by a combination of both. To prevent distortion of the flow pattern, geometric similarity in the sloping tunnel was maintained and velocity correction was obtained by eliminating a portion of the nearly horizontal uniform circular tunnel.

To determine the tunnel length correction, a velocity computation, Table 1, was made to determine the velocity at the outlet portal of the prototype tunnel for the maximum discharge of 53,000 second-feet. The morning-glory spillway had been designed so that the throat at elevation 3523 was a control and was to flow full with a negative head of 6.4 feet for the maximum discharge of 53,000 second-feet. Computations were started at the control using a roughness coefficient "n" for the prototype of 0.014. Bend loss in the upper bend was estimated to be approximately 8 feet of water and in the lower bend to be negligible since it did not flow full. The velocity at the outlet portal of the spillway was computed to be 146.4 feet per second.

The velocity at the outlet portal of a complete 1:36 scale model of the spillway tunnel was computed in Table 2 in the same manner as for the prototype, making the same assumptions except for the roughness coefficient "n" which was assumed to be 0.010 for the plastic model. The computed velocity at the outlet portal of the model was 22.06 feet per second which, in accordance with Froude's law, is equivalent to 132.36 feet per second in the prototype.

In order to increase the velocity at the outlet portal in the model so that it would more truly represent the prototype, some of the uniform circular section downstream from the lower bend was eliminated. As much of this section was omitted in the model as believed possible without affecting the flow patterns throughout the lower bend and horseshoe transition. Therefore, 60.17 inches of the uniform circular section, extending downstream from the lower bend, was eliminated leaving only a 23-inch model length. The velocity of the model was then computed in Table 3 to be 23.18 feet per second which corresponds to 139.1 feet per second in the prototype. Since it was not desirable to eliminate other portions of the tunnel, it was believed that this value of 139.1 feet per second was sufficiently close to the computed prototype value of 146.4. Therefore, the spillway tunnel was modeled in this manner.

Flow characteristics. The spillway in operation was observed for discharges ranging from 10,000 second-feet to the maximum of 53,000 second-feet. Flow characteristics at the crest of the morning-glory for discharges of 53,000, 30,000, and 10,000 second-feet are shown in Figures 21 and 22. Flow characteristics through the upper bend, inclined tunnel, and lower bend are shown in Figures 23 and 24 for discharges of 53,000, 30,000, and 10,000 second-feet each with the ring gate seated.

(a) 53,000 second-feet.--For 53,000 second-feet, the morning-glory was well filled by the flow as shown in Figures 21c and 22c. Vents under the lip of the gate did not function properly because water entered the vents in the vicinity of the control pier filling the air chamber with water. This condition occurred in a region extending almost 90° to the right and left of the pier. Pressures recorded in the vicinity of the air vents will verify this condition as discussed in a later section on pressures.

For 53,000 second-feet through the inclined portion of the tunnel shown in Figure 23b, the flow surged at irregular intervals. Momentarily, parts of the inclined tunnel filled completely, causing a surge in the morning-glory entrance. Flow through the tunnel zigzagged slightly from side to side and had a tendency to spin over the crown of the tunnel. The zigzag was not nearly so prominent for this flow as for smaller discharges since the throat of the morning-glory was completely filled.

Immediately downstream from the lower bend a "dishing" effect of the water surface occurred. Centripetal force caused the water flowing from the lower bend to climb the tunnel walls to meet at the crown, causing a spray that partially, and sometimes completely, sealed the tunnel, as shown in Figure 23c. In the horseshoe transition and horseshoe section downstream, the tunnel was only partially filled, but the flow was rough and irregular.

(b) 30,000 second-feet.--For 30,000 second-feet with the gate seated, the air vents again failed to function properly as the air chamber again filled with water in the same manner as for 53,000 second-feet. Flow through the morning-glory was not symmetrical, due to the spillway approach conditions as previously discussed in the spillway approach section; therefore, the flow zigzagged through the tunnel spiraling over the top in some places as shown in Figure 24a. Except for the zigzag effect the flow through the tunnel was fairly uniform and free of surging. At no place did the tunnel completely fill with water. The dished flow pattern existed downstream from the lower bend, but the tunnel was not completely sealed with water spray at that point.

Maintaining the flow at 30,000 second-feet and elevating the gate until the reservoir reached maximum elevation increased the prominence of the zigzag flow. With the gate in this position, water did not flow into the air chamber as it did before, but the venting system still failed to function because the demand for air was small in the region of the air vents as was proven by the pressure data recorded and discussed later in this section.

(c) 10,000 second-feet.--The behavior of the flow in the spillway was the same for 10,000 second-feet as for 30,000 second-feet, except that the zigzagging of the flow was more prominent as can be seen clearly in Figure 24b. The zigzag flow plus the dishing effect caused the flow to spin completely over the top of the tunnel downstream from the lower bend.

Calibration. Model calibration tests showed the spillway to discharge approximately the maximum discharge of 53,000 second-feet with the ring gate seated for maximum reservoir elevation 3564.9. However, for any given reservoir elevation below the maximum, the discharge curve obtained from model calibration test data does not show as much discharge as does the computed curve shown in Figure 26.

The efficiency of the Hungry Horse morning-glory crest at the maximum design flow of 53,000 second-feet was determined from the model calibration test data by computing the coefficient of discharge in the equation:

$$Q = CLH^{3/2}$$

where Q is the total discharge, L is the circumference of the 64-foot-diameter crest line, and H is the difference in elevation between the crest and the water surface of the reservoir. The coefficient was computed to be 3.79 for the maximum design flow which indicates an efficient design. However, the coefficient might have been even higher if the morning-glory could have had radially approaching flow instead of the tangentail flow, and if the control pier could have been eliminated. Pressures recorded in the morning-glory showed that excessive subatmospheric pressures existed on the ring gate and in the morning-glory throat as shown in Figure 27 and as discussed in the following section on pressures. These subatmospheric pressures undoubtedly aided greatly in producing a high discharge coefficient.

Pressures. Piezometers for measuring pressures throughout the morning-glory structure were located as shown in Figure 13. Piezometers along the invert and crown of the tunnel were located as shown in Figure 8. Exhaustive tests were conducted throughout the course of the investigation to record the pressures at these piezometers. The data from the more significant of these tests are recorded in Table 4.

(a) Pressures in the morning-glory throat.--Excessive subatmospheric pressures occurred around the circumference of the morning-glory throat for flows of 53,000, 40,000, 35,000, and 30,000 second-feet either with the gate seated as recorded in Table 4 in Tests 1, 22, 26, and 5, respectively, or with the gate elevated to provide maximum reservoir elevation as recorded in Tests 12, 24, and 11 for flows of 40,000, 35,000, and 30,000 second-feet, respectively. The excessive subatmospheric throat pressures were indicated by Piezometers 8, 9, 20, 21, 22, 30, 31, 42, 43, and 44 located as shown in Figure 13. The subatmospheric pressures were most severe for the maximum flow of 53,000 second-feet, as shown in Figure 27 on the crown side of the morning-glory along the tunnel center line. Figure 27 also shows the pressures along the crown and invert sides of the morning-glory for discharges of 30,000 and 10,000 second-feet. At Piezometers 43 and 44 on the crown side in the throat of the morning-glory the pressures were 32 feet of water below atmospheric for 53,000 second-feet. For flows as low as 30,000 second-feet, the pressures were still 11 feet below atmospheric in this region; and for 30,000 second-feet with the gate elevated, pressures were 9 feet below atmospheric.

(b) Pressures near the air vents under the gate lip.--The subatmospheric pressures in the throat were due, to some extent, to the failure of the venting system to function, while the failure of the venting system was due to the existence of greater than atmospheric pressures in the region of the vents. The vents were located in the crest structure under the gate lip as shown in Figure 13. In the region of these vents pressure measurements were made at piezometers (5, 14, 27, 36, 45, and 46) which are recorded in Table 4 for various magnitudes of flow. All pressures show that there is little or no demand for air in the region of the vents. Pressures at Piezometers 46 and 5 show that the vents located farthest from the control pier are in the more favorable position, but even here the air demand is low.

At Piezometers 26 and 27, located in front of the control pier immediately above and below the lip of the ring gate, pressures were above atmospheric for all flows with the gate seated. This indicated that water stood under the gate lip in this region and, therefore, entered the vents. So much water entered these air vents that the air chamber circling the interior of the crest was soon filled with water. With the chamber full of water it was impossible for any of the vents to function. To prevent water from entering the air chamber, the vents located approximately 90° to the right and left of the control pier were sealed. The remaining vents still failed to function due to the fact that the vents were located in a region on the crest profile where little or no demand for air existed. For flows with the ring gate elevated, subatmospheric pressures were sufficient to allow the air vents located farthest from the control pier to function, as is evidenced by Pressure Tests 12, 24, and 11 recorded in Table 4. However, even then the vents did not provide as much ventilation as was necessary to relieve subatmospheric pressures in the lower throat region of the morning-glory.

(c) Pressures on the gate crest.--Excessive subatmospheric pressures occurred on the gate crest as is evidenced by the pressures recorded at Piezometers 2, 3, 4, 11, 12, 13, 33, 34, and 35 in Tests 1, 22, 26, 5, 12, 24, and 11 recorded in Table 4. Greatest subatmospheric pressures were recorded at Piezometers 2 and 3 which were located 90° to the left of the center line of the tunnel or nearly directly across the morning-glory from the control pier. Here, a subatmospheric pressure of 17 feet of water was recorded in Test 1 for 53,000 second-feet discharge. Pressures were considerable below atmospheric on the ring gate crest for all discharges of 30,000 second-feet or more with the gate seated or with the gate elevated as shown by the recorded pressures in Table 4. Subatmospheric pressures at Piezometers 33, 34, and 35, located on the crown side of the morning-glory, were somewhat less than those recorded at 2, 3, and 4. Still, a pressure of 13.5 feet of water below atmospheric was observed at Piezometer 34 for 53,000 second-feet. Figure 27 shows graphically the pressures at Piezometers 11, 12, 13, 33, 34, and 35 for flows of 53,000, 30,000, and 10,000 second-feet.

(d) Pressures in the tunnel.--Another region of excessive subatmospheric pressures was indicated by the tunnel piezometers. This region extended along the crown of the tunnel from the morning-glory throat through the upper and lower bends to the point at which the tunnel was sealed by the dished flow pattern discussed earlier. Piezometers 56, 57, and 58 through the upper bend showed pressures as low as 37 feet of water below atmospheric to exist for 53,000 second-feet, as recorded in Test 17 in Table 4 and shown in Figure 28a. Piezometers 59 through 71 which were located in the crown of the inclined tunnel, the crown of the lower bend, and the crown of the nearly horizontal tunnel showed subatmospheric pressures as much as 23 feet of water at the upper end of the incline, 25 feet of water in the lower bend, and 25 feet of water in the horizontal portion at Piezometer 70.

Since the flow surged through the incline, momentarily filling portions of the tunnel, the pressures along the crown fluctuated from atmospheric to the subatmospheric values recorded in Table 4 for 53,000 second-feet. Apparently the high velocity flow through the tunnel pulled air with it from the upper bend and inclined portion of the tunnel to cause the subatmospheric pressure condition. This air was not immediately replaced, since the vents under the gate lip failed to function and since the dishing effect downstream from the lower bend apparently sealed the tunnel, preventing ventilation from the outlet portal. For 53,000 second-feet, excessive subatmospheric pressures in the tunnel caused air to be drawn in at irregular intervals through either the dished flow or through morning-glory vortices. Thus, the air was partially replaced at irregular intervals which caused the surging flow in the tunnel and the fluctuating pressures along the crown.

Pressures on the crown of the tunnel, downstream from the point at which the dishing flow pattern occurred, were atmospheric for the maximum flow of 53,000 second-feet. This indicated that the tunnel downstream from the dished flow pattern received continuous ventilation from the outlet portal while the portion of tunnel upstream did not.

For flows of about 35,000 second-feet and less, pressures in the tunnel were only slightly below atmospheric except in the upper bend. Immediately below the morning-glory the subatmospheric pressure was 10 feet of water on the crown side as shown by Tests 26 and 19 recorded in Table 4. Surging flow did not occur for these smaller discharges; thus, the pressures were quite steady.

Pressures along the tunnel invert were approximately atmospheric in the upstream half of the incline, becoming slightly greater than atmospheric in the lower half, as recorded in Test 17 in Table 4 and shown in Figure 28a for 53,000 second-feet. On the invert of the lower bend, pressures were considerably above atmospheric. At one point the centrifugal force of the flow produced 180 feet of water pressure. On the invert of the horizontal portion of the tunnel, the pressures subsided to approximately 15 feet of water above atmospheric.

<u>Summary.</u> The preliminary spillway was capable of discharging the maximum flow with the reservoir at maximum elevation at the expense of excessive subatmospheric pressures on the gate crest, in the morning-glory throat, and throughout most of the tunnel. The subatmospheric pressures, to some extent, were due to the failure of the

undernappe vents to function and the failure of the tunnel to receive adequate ventilation from the outlet portal or the morning-glory. The undernappe vents failed because the vents were located in a region of atmospheric pressure or above.

For the maximum discharge, flow through the tunnel was very erratic, with surges sufficient to momentarily fill portions of the tunnel incline completely. Downstream from the lower bend the tunnel was sealed with spray from a "dishing" flow pattern caused by centripetal force of the lower bend in turning the direction of flow. The spray from the dished flow sealed the tunnel, preventing ventilation from the outlet portal except possibly at irregular intervals.

For smaller flows of about 35,000 second-feet and less, the throat of the morning-glory was not completely filled and surging or severe subatmospheric pressures did not exist in the tunnel except in the upper bend and in the morning-glory throat. But for these smaller flows, a zigzag flow pattern persisted throughout the tunnel from the upper bend downstream. This flow pattern which was due to the bulk of the flow entering the morning-glory to the right of the tunnel center line was most pronounced with the ring gate elevated.

Problems to be solved in further investigation of the morning-glory crest and tunnel appeared to be as follows: (1) elimination of erratic surging flow in the tunnel that occurred for discharges near maximum, (2) elimination of the severe subatmospheric pressures in the morning-glory and tunnel, (3) straightening of the zigzag flow through the tunnel, and (4) reduction of the dishing of the flow downstream from the lower bend. Various proposals were made to help solve these problems including: (1) abandonment of the morning-glory crest in favor of a radial gate controlled overflow crest, (2) a larger diameter morning-glory crest with a larger throat, (3) a revised crest shape for the morning-glory, (4) radial entrance piers on the crest profile, (5) a deflector in the throat above the crown of the upper bend, (6) a revised venting system including an additional vent in the crown of the upper bend near the throat, (7) a larger diameter tunnel, (8) a longer radius of lower bend, (9) flow straightner guide vanes in the upper bend, or (10) combinations of any of these suggestions. Of these proposals, numbers (3), (6) and (8) were adopted for the prototype structure. The laboratory felt that proposals (1), (7) and (9) were also desirable, but these were objected to by the designers because of structural limitations. The addition of entrance piers to the preliminary crest was tried first, since this involved no changes to the model structure.

First Step--Preliminary Morning-glory with Radial Piers on Crest

The first step to improve the performance of the spillway was to add radial piers to the morning-glory crest as shown in Figure 29a. The piers were the same height as the control pier and 15 feet wide. They were placed on the crest over the ring gate. In the prototype the piers could be slotted to receive the ring gate or the ring gate could be replaced by radial gates between the piers.

It was believed that the piers would aid in producing entrance flow conditions similar to radial flow and operation of the model showed this theory to be true. Operation with the piers in place for 53,000 second-feet passing over the spillway is shown in Figure 30. The piers guided the flow entering the spillway toward the center of the morning-glory. The flow was more evenly distributed around the circumference of the morning-glory; therefore, the flow entered the tunnel nearly symmetrical about its axis. As a result, zigzag flow through the tunnel was almost nonexistent for the low flows as well as for the high flows. However, for flows near maximum, the erratic surging still occurred because apparently the tunnel still failed to receive adequate ventilation from either the entrance end or the outlet end of the tunnel. Vents under the gate lip did not function and ventilation from the outlet end was again hampered for the high discharges by the dishing flow pattern and resulting spray downstream from the lower bend.

Pressures in the region of the air vents were again above atmospheric or only slightly below; while pressures recorded on the ring gate crest, in the morning-glory throat, and on the crown of the upper bend and inclined tunnel were again very much below atmospheric as recorded for 53,000 second-feet in Test 4, Table 4 and plotted in Figure 28a.

For a discharge of 53,000 second-feet, the reservoir elevation was more than a foot above the maximum desired water surface; consequently, the capacity of the spillway at maximum head was reduced. The reduced capacity was probably caused by the shorter crest length which resulted from the additional piers.

The water surface elevations on the two sides of each pier were very unequal except at the one pier located directly across the morning-glory from the control pier. The water surface on the reservoir side of the piers was higher than normal, while the water surface on the shoreward side was drawn below normal by a flow contraction as shown in Figure 30.

Since the piers did not affect the subatmospheric pressures and they did not prevent the erratic surging that accompanied the very high discharges, they were not recommended for prototype construction. The piers did help, however, to straighten the flow through the tunnel; so, it was felt that some type of pier might be used for flow straighteners while other means might be utilized to eliminate subatmospheric pressures and surging flow.

<u>Second Step--Preliminary Morning-glory with 2.6-foot diameter Vent in Crown of Upper Bend</u>

In the second step, an attempt was made to eliminate or reduce subatmospheric pressures as well as the surging flow conditions throughout the spillway. An air vent 2.6 feet in diameter was provided in the crown of the upper bend near the throat of the morning-glory. This vent, 5.31 square feet in area, was located at elevation 3514.95 on the center line of the crown of the upper bend just below Piezometer 56.

Model views of 53,000 second-feet of water flowing through the structure are shown in Figure 31. The effect of the air vent was apparent; the flow broke free of the tunnel crown as shown in Figure 31b, whereas in the preliminary design the upper bend flowed full as shown in Figure 24a. Flow through the inclined tunnel was much steadier than without the air vent, but the flow still zigzagged from side to side and surged a trifle for the maximum discharge. The vents under the ring gate still failed to function and the dishing flow condition again occurred just downstream from the lower bend preventing ventilation of the inclined tunnel from the outlet portal as shown in Figure 31d. For flows of 30,000 second-feet and less, the zigzagging flow pattern through the tunnel was as pronounced as for the preliminary crest and tunnel without the air vent.

Pressures throughout the structure were measured for the gate seated and are recorded in Table 4 in Tests 10, 16, 21, and 23 for discharges of 53,000, 40,000, and 30,000 second-feet. For 53,000 second-feet, subatmospheric pressures were slightly reduced on the gate crest but pressures in the vicinity of the throat of the glory hole remained approximately the same with or without the vent as shown in Figure 28a. On the crown side of the upper bend, immediately above and below the air vent, subatmospheric pressures were greatly reduced, as indicated by Piezometers 56 and 57, but other pressures along the crown of the upper bend and the inclined tunnel were more subatmospheric than without the vent. Pressures along the invert of the inclined tunnel were now subatmospheric, whereas before the vent was installed, they were not. Several explanations were advanced to explain the unexpected occurrence.

One explanation for this drop to greater subatmospheric pressures in the crown and invert of the incline tunnel is as follows: Since air is drawn in through the vent near the throat of the morning-glory, the upper bend below the throat did not flow full as occurred without the vent. Therefore, the reservoir raised 1 foot higher than maximum reservoir elevation, as shown by the calibration curve in Figure 26, in order to provide enough head to pass 53,000 second-feet through the upper bend. The higher head and smaller cross-sectional area of water in the upper bend produced higher velocities through the upper bend and the inclined portion of the tunnel; and, therefore, created a demand for air which was greater than the capacity of the 2.6-foot-diameter air vent, resulting in lower subatmospheric pressures. This theory seemed probable when in later tests the area of the air vents was tripled, providing an air supply which exceeded the demand. Subatmospheric pressures on the crown of the incline then became near-atmospheric and those on the tunnel invert were atmospheric or above.

Another plausible explanation was as follows: Without the vent in the upper bend, air entered the spillway in bursts through the morning-glory entrance which served to relieve the subatmospheric pressures throughout the tunnel to a certain extent. With the air vent installed, subatmospheric pressures were relieved considerably in the throat control region immediately above the air vent as shown by Piezometer 56 in Figure 28a. This resulted in less negative head and a higher reservoir elevation. The higher reservoir submerged the crest shown in Figure 31a to the extent that air no longer entered the spillway from above which more than offset the air supplied through the vent.

For 30,000 and 40,000 second-feet the pressures on the morning-glory crest were almost identical to those recorded in the preliminary design as shown in Table 4. Compare Tests 22 and 5 with Tests 21 and 23, respectively. These same tests also show that subatmospheric pressures on the crown of the upper bend, as well as the crown of the complete tunnel, were relieved somewhat by the installation of the air vent for these smaller flows.

Spillway calibration data plotted in Figure 26 show the capacity of the spillway at maximum reservoir elevation to be reduced to about 49,600 second-feet. Apparently, air that reduced the subatmospheric pressures around the vent in the upper bend also reduced the negative head that previously aided the discharge. For 30,000 second-feet and less the reservoir elevation was the same with or without the air vent.

To summarize the results of this step: The 2-foot, 6-inch-diameter air vent was well located for supplying air to the tunnel but was too small. Therefore, it did more harm than good so far as eliminating or reducing subatmospheric pressures throughout the tunnel. The vent was of no aid in reducing subatmospheric pressures in the morning-glory throat; it did not help in eliminating the zigzagging flow pattern; it did not affect the concave dishing of the flow downstream from the lower bend; but, it did eliminate most of the erratic surging through the inclined tunnel which previously occurred for the very high discharges.

Third Step--Preliminary Morning-glory with Three 2.6-foot-diameter Vents in Crown of Upper Bend

In the third step the area of the air vent in the crown of the upper bend was increased to 15.93 square feet by the addition of two more 2.6-foot-diameter air vents located directly below the first. Operation with 53,000 second-feet flowing through the structure with this modification is shown in Figure 32.

Pressures are recorded in Test 28 in Table 4 for a discharge of 53,000 second-feet and plotted in Figure 28b. The pressure was still 23 feet of water below atmospheric at Piezometer 43 on the crown side of throat; however, subatmospheric pressures in the throat of the morning-glory were not as severe as for the preliminary design without the vent. Pressures along the crown of the upper bend, inclined tunnel, and lower bend were approximately the same as for the preliminary design but not as severe as when the single vent was used. Along the invert of the inclined tunnel pressures were atmospheric or above as was the case for the preliminary design. Apparently, the increased area of the vent or the lower location of the two added vents was helpful in relieving subatmospheric pressures in the tunnel.

The vents in the upper bend also reduced pressures in the upper bend at Piezometers 56 and 57 immediately above and below the vents which in turn reduced the negative head that aided in increasing the discharge of the morning-glory. Therefore, the discharge was reduced to 49,000 second-feet for the maximum reservoir as shown in Figure 26. For 53,000 second-feet the increased depth of water on the morning-glory apparently reduced the amount of subatmospheric pressure on the ring gate and morning-glory profile. Vents under the ring gate crest still failed to function when the gate was seated and functioned poorly when the gate was raised.

For lower discharges, the flow zigzagged through the tunnel as before. For the maximum discharge of 53,000 second-feet, the concave dishing of the flow still occurred downstream from the lower bend which apparently still prevented ventilation of the inclined tunnel from the outlet portal.

<u>Fourth Step--Preliminary Morning-glory with Six 2.6-foot-diameter Vents in Crown of Upper Bend</u>

The fourth step was to double the area of the previous air vent or to provide 31.86 square feet of vent area by the addition of three more 2.6-foot-diameter air vents in the crown of the upper bend near the morning-glory throat. For 53,000 second-feet, subatmospheric pressures were reduced a little more but they were still excessive around the throat circumference of the morning-glory, being as much as 19 feet of water below atmospheric. Subatmospheric pressures still occurred along the crown of the upper bend and inclined tunnel but were now about 8 feet of water or less as compared to 20 feet of water with one-half of the vent area. The pressures for a discharge of 53,000 second-feet are recorded in Test 38 in Table 4 and plotted in Figure 28b.

For maximum discharge, the reservoir elevation was approximately 3 feet too high as shown by the calibration curve in Figure 26. The discharge for maximum reservoir was approximately 48,200 second-feet. For this discharge, pressures were not quite as adverse as for 53,000 second-feet, but they were still considered to be too severe.

The flow conditions were very similar to those with only one-half the venting area. The flow still zigzagged through the tunnel for the lower discharges and the dishing effect still occurred.

Fifth Step--Preliminary Morning-glory with Six 2.6-foot-diameter Vents in Upper Bend and Five Radial Piers Outside of Ring Gate Circumference

Five radial piers were placed outside of the ring gate circumference as shown in Figure 29b. The piers were placed outside to avoid interference with operation of the ring gate. These piers were used primarily as flow straighteners to eliminate the zigzag through the tunnel. The venting area in the upper bend remained unchanged from that of the previous step. Flow through the structure for a discharge of 53,000 second-feet is shown in Figure 33.

Pressures for a discharge of 53,000 second-feet were recorded in Table 4, Test 40, and are plotted in Figure 28b. Subatmospheric pressures were still excessive in the throat of the morning-glory, being about the same as without the piers. Pressures in the crown of the incline were slightly more subatmospheric than without the piers.

The discharge at maximum reservoir elevation was approximately 52,000 second-feet as shown by the calibration curve in Figure 26. The zigzag flow pattern was partially corrected. Piers in the model were made so that each one could be pivoted to its most effective angle. By properly setting the piers, the zigzag could be almost entirely eliminated for some flows, while for others no improvement was gained. When the piers were set at the most effective angle to eliminate the zigzag, draw-down around the piers was greater and, therefore, more undesirable. They were not recommended for the prototype.

Sixth Step--Preliminary Morning-glory with Tunnel Removed

The sixth step was to test the preliminary crest with the tunnel removed from the morning-glory at throat elevation 3520. The purpose of this step was to determine the capacity of the morning-glory and the subatmospheric pressures in the throat when there was atmospheric pressure in the tunnel.

The investigation revealed that at maximum reservoir elevation the discharge was reduced to 47,300 second-feet as shown by the calibration curve, Figure 26. The head on the crest necessary to pass the maximum design flow of 53,000 second-feet was then increased about 3.6 feet. Since the crest was submerged more than ever before to pass the design flow, subatmospheric pressures were almost entirely eliminated on the gate crest and were reduced to not more than 16 feet of water below atmospheric pressure in the morning-glory throat as shown in Figure 28b and recorded in Test 45 in Table 4.

For a discharge of 53,000 second-feet the maximum subatmospheric pressure in the throat of the glory hole was reduced from

19 feet of water, with the six air vents, to 16 feet of water. For a discharge of 47,300 second-feet, subatmospheric throat pressures still measured as much as 12 feet of water.

This study indicated that additional venting in the upper bend would improve pressures in the throat of the morning-glory crest only a small amount and in turn would reduce the maximum capacity of the spillway by more than 10 percent. Additional venting of the upper bend with the tunnel in place would therefore be ineffectual.

Seventh Step--Preparations for Developing the Crest Profile by Use of the Circular Weir Model

From the preceding experiments it was deemed impossible to vent the tunnel at the crown of the upper bend sufficiently to eliminate severe subatmospheric pressures in the throat of the morning-glory. Therefore, to obtain satisfactory operation, either a venting scheme that would function should be installed some place above the throat, or the crest shape should be revised to reduce the need for air, or both. A vent circling the morning-glory throat at about the elevation of Piezometer 43 was contemplated, but it appeared that the shape and perhaps the size of the morning-glory crest should be improved. It was decided to try other crest shapes and morning-glory sizes.

In order to determine a satisfactory crest shape for the Hungry Horse Spillway, a decision was made to construct a sharp crested circular weir, Figure 18, from which of the undernappe surface profiles could be obtained for any desired head and any desired magnitude of subatmospheric pressure under the nappe. It was evident that a certain amount of subatmospheric pressure on the crest profile was necessary in order to discharge 53,000 second-feet without increasing the head on the crest or the size of the morning-glory.

The first profiles to be obtained from the circular weir were to be for radial flow approaching the weir. It was felt that these could be modified later if necessary to adjust for the tangential flow conditions at Hungry Horse.

Subsequent tests showed this procedure to be correct. A satisfactory profile was developed from the circular weir tests which made use of controlled subatmospheric pressures beneath the nappe. However, testing was continued and an exhaustive research study of the circular weir was made. The tests necessary to understand the development of the Hungry Horse profile are discussed in Step 11 of this report. The complete weir study is reported in ASCE Proceedings[1].

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[1] ASCE Proceedings, Vol. 80, Separate No. 432, "Morning-glory Shaft Spillways Determination of Pressure-controlled Profiles" by W. E. Wagner, Bureau of Reclamation, dated April 1954.

Since construction of the circular weir model would require considerable time, it was also decided to proceed with the testing of various spillway shapes in the spillway model using the cut and try method of obtaining the profile. These tests are discussed in Steps 9 and 10.

Eighth Step--Development of the Tunnel

At this juncture in the investigation, while the circular weir was being constructed, it was necessary to approve or disapprove the preliminary tunnel design because excavation of a pilot tunnel in the prototype spillway had already begun. Therefore, the eighth step in the studies was to analyze and to improve if possible the flow characteristics through the inclined tunnel, lower bend, and horizontal tunnel. Since five additional piers around the outside circumference of the ring gate straightened the flow through the tunnel better than any other scheme tested thus far and since six 2.6-foot-diameter air vents in the crown of the upper bend provided more ventilation to the tunnel than any other scheme thus far tested, this arrangement of the model at the morning-glory entrance and in the upper bend was used for the following investigation of flow through the inclined tunnel, lower bend, and horizontal section.

Preliminary short radius lower bend. The preliminary lower bend with a radius of 55 feet is shown in Figure 34a. From the studies thus far, that portion of the horizontal tunnel which extended downstream from the horseshoe transition section seemed adequate, but the portion between the transition and the bend was almost completely filled with water and spray from the dished flow pattern. Even for discharges as low as two-thirds of maximum capacity or 35,000 second-feet, this portion of the tunnel was almost completely filled with water and spray. It was believed that improvement of this flow condition would provide better ventilation of the inclined tunnel. It was important to provide as much ventilation to the inclined tunnel as economically possible since pressures on the crown of the incline were still a few feet below atmospheric for the maximum flow even with the six 2.6-foot-diameter air vents in the upper bend as recorded in Test 40 in Table 4 and shown in Figure 28b.

The tunnel downstream from the bend was changed as shown by alteration No. 1 in Figure 8. A portion of the 24.5-foot-diameter tunnel had originally been omitted in the model to provide higher velocities at the outlet portal as discussed earlier in the description of the preliminary morning-glory spillway. It was now more important to have the horizontal tunnel more truly represented in the model so that the effects of the dished flow pattern could be better evaluated. Piezometer locations in this altered horizontal tunnel are shown in Figure 8.

For 53,000 second-feet the horizontal tunnel, with this additional uniform circular section installed, was filled with spray for a much longer length than when the horseshoe transition was used; compare Figure 35a with 33d. Due to the more complete sealing of the tunnel with spray, the pressures along the crown through the incline were a little more subatmospheric than when the horseshoe transition was in place; compare the pressure data of Test 40 with that of Test 53 in Table 4. The greatest subatmospheric pressure in the tunnel now was 13 feet of water at Piezometer 70 in the crown of the horizontal tunnel 107 feet downstream from the P. T. of the lower bend. This piezometer was near the point of maximum dishing effect of the flow.

Recommended long radius lower bend. The radius of the lower bend was increased from 55 feet to 120 feet as shown in Figure 34b. Piezometers in the model bend are located as shown in alteration No. 2 in Figure 8.

For a discharge of 53,000 second-feet the degree of dishing was greatly reduced as shown by comparison of Figures 35a and b. As a result of the reduced dishing effect the crown of the tunnel upstream was better ventilated as found by comparing pressures recorded in Tests 53 and 55, Table 4. The subatmospheric pressures along the crown of the incline were reduced from 9 feet of water to approximately 7 feet of water while the subatmospheric pressure on the crown of the tunnel above the dished flow pattern at Piezometer 70 was reduced from 13 feet to only 5 feet of water below atmospheric. A comparison of Figures 35c and d shows an even greater improvement of the flow appearance for 35,000 second-feet.

It was felt that a larger diameter tunnel in the lower bend and throughout the uniform circular horizontal section, in addition to the long radius bend, would have nearly eliminated the dishing effect for 53,000 second-feet. It was felt, too, that the larger diameter would provide more room for bulking of the flow due to air entrainment that occurs in prototypes but not in models; but because excavation for the horizontal portion of the tunnel was fairly near to completion, it was not the desire of the designers to increase the size of the tunnel unless absolutely necessary. Therefore, the long radius lower bend was recommended for the prototype without change in tunnel diameter.

Lower bend with square cross section and short radius. At this point in the study it was learned that the pilot tunnel through the preliminary 55-foot-radius lower bend of the prototype had been completed. Therefore, to prevent if possible, changing the radius of the lower bend, other means were tested to improve the flow conditions through the lower bend and the tunnel downstream. With the radius of the bend at 55 feet, the tunnel was changed to a square section whose sides were the same length as the diameter of the circular section. Square to circular tunnel transitions extended upstream and downstream from the bend as shown in Figure 34c. This modification increased the cross-sectional area of the tunnel through the lower bend and it was hoped that perhaps the square sides of the bend would tend to prevent the flow from climbing the sides of the tunnel downstream.

For flows of 50,000 and 35,000 second-feet the dishing effect was not improved; instead, flow was not as smooth through the square tunnel section of the lower bend and transition as through the preliminary circular section. Therefore, this design was abandoned and the 120-foot-long radius bend previously tested was adopted for the prototype structure.

Ninth Step--Second Morning-glory Crest and Second Upper Bend

Description. While work progressed on the construction of the sharp-crested circular weir model, the second and third morning-glory crest shapes were installed and tested in the Hungry Horse Spillway model. The second crest is shown in Figure 25. The crest was at the same elevation as the preliminary crest but had a crest spring point diameter of 80 feet as compared to 68 feet in the preliminary design. The ring gate, unlike the preliminary gate, was a sharp-crested circular weir which when seated was below the undernappe of the flow over the fixed crest. With the gate elevated 1 foot so that the gate crest was at the fixed crest elevation of 3548, the spring point shifted to the gate crest which was the same diameter as the preliminary crest. The lowermost point in the throat of the morning-glory was at elevation 3528 which was 8 feet higher than in the preliminary design and the throat diameter was 50 feet as compared to 34.79 feet in the preliminary morning-glory crest.

The upper bend for this crest is shown in Figure 34e as the second upper bend design. An air duct circled its upper end with fifty 2-foot-diameter vents opening into the upper bend, as shown in Figure 25. The vents were staggered in two rows and equally spaced.

The purpose of this design was to eliminate the morning-glory throat control where subatmospheric pressure was found to be excessive in the preliminary morning-glory. The sharp-crested ring gate was to cause the nappe to spring free of the spillway profile so that the undernappe could be aerated by the vents circling the upper bend. The 80-foot-diameter fixed crest was to provide a morning-glory crest sufficiently long to discharge the maximum flow of 53,000 second-feet with atmospheric undernappe pressures.

Flow characteristics in morning-glory. First observations were made without the upper bend and inclined tunnel. With the gate seated, the undernappe of the flow failed to spring free at the crest for any discharge. The undernappe instead followed the crest profile and, therefore, was not ventilated, as shown in Figure 36a for 53,000 second-feet. The undernappe could, however, be made to spring free in the model by momentarily placing any sizable object in the nappe of the flow over the crest. The object provided an opening in the nappe through which air entered to the underside. Once the undernappe was ventilated it would remain so after the object was removed, since the undernappe was open to the atmosphere as shown in Figure 36b.

The undernappe could also be vented by elevating the ring gate about 0.18 foot above the fixed crest elevation of 3548, provided the head on the weir was 5.5 feet or more. With the gate elevated the nappe sprang from the gate weir crest, but if the gate was reseated the spring point shifted back to the fixed crest and the undernappe again adhered to the morning-glory walls.

Attempts were made to vent the undernappe by means other than elevating the gate. First, radial piers similar to those used with the preliminary morning-glory shown in Figure 29b, were tested to determine whether the piers would provide gaps in the nappe through which air could enter to the underside; but, these piers failed to vent the undernappe as shown in Figure 36c for 53,000 second-feet. The piers were too narrow and too far upstream.

Flow characteristics in morning-glory with square nose control pier. A more successful method of venting the undernappe was tested after the tunnel was installed in the model. The pointed nose of the control pier was changed to a square nose. In theory the square nose was to form an air gap in the nappe through which air could enter from above to the underside of the nappe. This method was satisfactory if the gate crest was elevated 0.18 foot or more above the fixed crest when flow first started over the crest. When the head on the crest reached 3 feet the undernappe became ventilated; the gate could then be reseated and the discharge increased without disrupting the ventilation of the undernappe. A discharge of 53,000 second-feet entering the morning-glory with the gate reseated is shown in Figure 36d. Figure 37a shows 35,000 second-feet entering the morning-glory with the gate seated. Air entered the underside of the nappe through the gap formed by the square nose control pier and through the vents around the circumference of the upper bend, but it was the gap at the pier that first caused the nappe to spring free from the morning-glory.

Elevating the gate 0.18 foot above the fixed crest elevation reduced the capacity of the morning-glory to 47,500 second-feet for maximum reservoir. The capacity of the morning-glory with the gate seated and the undernappe ventilated was 62,000 second-feet. The tunnel capacity was designed for only 53,000 second-feet; therefore, the capacity of the morning-glory should not exceed that amount.

Pressures. Pressures in the morning-glory on the center line of the tunnel at the invert and crown side were measured first with the tunnel disconnected from the morning-glory and with the gate seated and the undernappe not ventilated. Pressures, in general, were below atmospheric for flows of from 35,000 to 53,000 second-feet as recorded in Tests 82 and 84, respectively, in Table 4, and as shown in Figure 38a for 53,000 second-feet. As much as 11 feet of water below atmospheric was recorded for 53,000 second-feet.

Pressures were measured also for flows of 35,000 and 53,000 second-feet with the gate seated and the undernappe ventilated. They were found to be either above atmospheric or only slightly below as recorded in Tests 81 and 83, respectively, Table 4, and shown in Figure 38a for Test 83.

With the tunnel attached, pressures for flows of 53,000 and 35,000 second-feet remained approximately the same or only slightly more subatmospheric. Pressures in the crown and invert of the upper bend and tunnel were checked and found to be above atmospheric on the invert and only slightly below atmospheric at the crown.

Flow characteristics in tunnel. With the upper bend and the remainder of the tunnel installed, flow characteristics throughout the tunnel were observed. A considerable amount of splash and swirl occurred in the upper bend, especially for flows under 50,000 second-feet. In fact, a considerable amount of water splashed through the 2-foot-diameter vents circling the upper bend near the throat, so, the vents were closed. By closing all the 2-foot-diameter vents throughout the structure the pressures became only slightly more subatmospheric. Figure 37b shows the swirl in the upper bend and the flow through the tunnel for a discharge of 35,000 second-feet with vents closed. As a result of the swirl that began in the upper bend, the flow zigzagged from side to side through the inclined tunnel and lower bend even more so than in the preliminary design. The zigzag flow pattern occurred for all discharges up to 53,000 second-feet, but was more noticeable for 35,000 second-feet with the gate elevated as shown in Figure 37d.

Flow characteristics in tunnel with guide vanes in upper bend. Attempts were made to reduce the splash and swirl in the upper bend and to eliminate the zigzag flow. The most successful method proved to be the addition of three guide vanes in the upper bend, beginning at throat elevation 3528 and extending into the inclined tunnel 60 feet beyond the end of the upper bend. One vane was located on the invert; the other two were located 60° to the left and right of the crown. The vanes were 4.5 feet high and could have been any thickness that was structurally practical; but because the most practical construction of the vanes in the model required the use of 1/4-inch plastic, the equivalent prototype thickness of the model vanes was 9 inches. The plastic vanes installed in the model can partially be seen in Figures 39a, b, and c.

Flow through the upper and lower bends was greatly improved as can be seen by comparing Figure 37 with 39. The sheet of water that previously swirled over the crown of the upper bend was completely eliminated by the swirl striking the vanes and turning inward to the center of the tunnel. Note that in Figure 39c the center of the guide vane on the invert of the tunnel is deflected considerably to the left by the force of the swirl which indicates it is effectively turning the water. A vane at this location in the prototype, of course, would need to be designed to withstand this force. Some swirl began even to the left of this guide vane, but this part was turned to the center of the tunnel by the next guide vane to the left. A smaller swirl which turned in the opposite direction from that of the larger one was directed to the center of the tunnel by the guide vane to the right of the invert. The flow after being directed to the center of the tunnel in the upper bend remained fairly well centered throughout the entire length of the tunnel. The flow pattern was improved for all discharges, but particularly so for discharges of about 35, 000 second-feet. However, the designers felt that the guide vanes, particularly the vane on the invert, would be too costly to construct and maintain since they are subjected to a very strong side thrust.

Conclusions. The second morning-glory crest was abandoned primarily because it was: first, a larger and more expensive structure than the preliminary design; second, it was capable of discharging more than the capacity of the tunnel; and third, it produced unsatisfactory flow through the tunnel unless guide vanes were used. A third morning-glory crest shape was tested in the next step.

Tenth Step--Third Morning-glory Crest with Vent Pier on Ring Gate and an 80-square-foot Vent in Recommended Upper Bend

Description. The third morning-glory crest devised and tested was a design more similar to the preliminary. It is shown in Figure 25. In the meantime, construction of the circular weir model continued.

The crest shape was similar to the preliminary, but with a larger throat diameter beginning at elevation 3537.57 and continuing down to elevation 3520 at the start of the upper bend. The throat diameter was 37 feet at elevation 3520 as compared to 34.79 feet for the preliminary. It was felt that a throat diameter of at least 37 feet was required to pass the maximum flow and provide space for ventilation of the undernappe. The vents under the gate lip of the preliminary design were omitted in this design in favor of a vent pier placed on the gate crest directly in front of the control pier. The nose of the control pier was revised so that it was square and as wide as the vent pier. The vent pier and revised control pier are shown in the model in Figure 40a.

The larger throat diameter made it necessary to revise the upper bend as shown by the recommended upper bend design in Figure 34f. An air vent was installed in the crown of the upper bend near the throat. The vent was a 4.50- by 17.76-foot slot which amounted to 80 square feet of opening. This area is considerably larger than the 31.86 square feet provided by the six 2.6-foot-diameter vents tested in the preliminary bend design in Steps 4 and 5.

Flow characteristics. The flow pattern throughout the tunnel was similar to that for the preliminary crest with the vent in the upper bend. The swirl and the zigzag flow pattern again occurred for discharges of 35,000 second-feet and less. Figures 40b, c, and d show the swirl and zigzag flow throughout the tunnel for 35,000 second-feet with the gate elevated. The swirl and zigzag were not nearly so prominent when the gate was seated.

The pier vent failed to aerate the undernappe for any discharge when the gate was seated, but ventilation occurred if the gate was elevated a foot or more. Ventilation did not occur with the gate seated because pressures on the crest of the gate in the vicinity of the vent pier were greater than atmospheric. Water, therefore, stood under the gate lip and prevented air from passing from the vent pier to the region of subatmospheric pressures on the opposite side of the morning-glory. With the gate elevated, the nappe near the control pier sprung from the gate lip to create a slight subatmospheric pressure immediately below the gate lip. An air passageway under the gate lip was thereby maintained from the vent pier to the region of larger subatmospheric pressure on the opposite side of morning-glory.

Certain combinations of head and gate elevation created a flutter in the nappe. Only flows of 30,000 second-feet or less were affected and those between 15,000 and 25,000 fluttered most. For 15,000 second-feet the nappe began to flutter when the gate was elevated 1.70 feet above its seated position. As the gate was elevated further the fluttering became more violent and was accompanied by a humming noise which was a maximum when the gate was elevated 2.00 feet. The fluttering stopped when the gate was elevated 3.20 feet above its seated position. For 25,000 second-feet fluttering began when the gate was elevated 0.95 foot; it was at a maximum and accompained by a roaring noise when the gate was elevated 1.50 feet. Fluttering stopped when the gate was 2.05 feet above its seated position. The fluttering was believed to be due to an unsteady supply of air to the undernappe. The nappe, when in contact with the spillway face, demanded air and received it from the vent pier; but once the undernappe received the air, it sprang free of the crest face reducing the demand for air. The nappe then depressed until it was in contact with the spillway face, and the cycle repeated.

The capacity of the spillway for maximum reservoir with the gate seated was approximately 51,000 second-feet. Elevating the gate to ventilate the undernappe reduced the capacity of the spillway still further, which in turn, reduced the amount of reservoir control.

Pressures. Pressures in the morning-glory, on the crown and invert sides, as well as along the crown of the upper bend for 53,000 second-feet with the gate seated, are recorded in Test 103 of Table 4. Pressures on the crown and invert sides of morning-glory are also shown in Figure 38b. Pressures were approximately the same as for the preliminary crest with 32 square feet of air vent area in the upper bend; compare Test 38 with Test 103 in Table 4 or in Figures 28b and 38b. The only appreciable difference is the fact that the point of greatest subatmospheric pressure occurred a little higher up in the morning-glory where the profile curved into the vertical throat.

With the gate elevated, the undernappe was ventilated; therefore, pressures along the crest profile became atmospheric. Pressures on top of the gate crest, however, were not reduced by elevating the gate but, instead, became more subatmospheric as shown in Test 105 in Table 4.

Conclusions. Subatmospheric pressures in the morning-glory were severe with the gate seated; but with the gate elevated sufficiently, pressures on the crest profile were reduced to approximately atmospheric because the 37-foot-diameter throat was large enough to permit the undernappe to spring free of the crest profile. Therefore, it would seem that the nappe would spring from the crest profile with the gate seated if the inside diameter of the morning-glory was increased from the ring gate down to the throat at elevation 3520. Consequently, it was decided not to change the throat diameter of 37 feet nor the crest line diameter of 64 feet but to reshape the crest profile between these two points. The throat diameter of 37 feet and the dimensions of the upper bend used here were adopted for the prototype at this time since the field construction forces had requested this information from the designers in order that excavation of the upper bend and morning-glory could proceed on schedule.

Eleventh Step--Development of the Recommended Crest Profile

At this stage of the study the sharp crested circular weir model shown in Figures 18, 19, and 20 had been completed and was ready for use in determining the shape of the crest profile for the morning-glory. The diameter of the sharp edge of the circular weir was assumed to be the outside or spring point diameter of the morning-glory crest which was 68 feet. The diameter of the circular weir in the model was 1.6608 feet; thus, the scale of the model was fixed at 1:40.94. The circular weir in operation is shown in Figure 41. The maximum flow, 53,000 second-feet, was discharged over the weir and the pressure regulating valves adjusted to produce atmospheric pressure under the nappe. The profile of the undernappe surface was determined and plotted as shown in Figure 42. The diameter of the jet at elevation 3520 measured approximately 36 feet which is within the allowable throat diameter of 37 feet that was established in the preceding step. The diameter of the highest point on the undernappe profile measured 64 feet as anticipated, and was labeled elevation 3548 since that was to be the crest line elevation. The elevation of the sharp-edged weir measured exactly 1 foot lower than the highest point of the undernappe profile and the head on the sharp-edged weir measured 18.50 feet. Therefore, the reservoir elevation was 17.50 feet above elevation 3548 which is 0.6 of a foot above the maximum allowable water surface, elevation 3564.9.

To lower the maximum reservoir elevation to 3564.9, it was necessary to either reduce the maximum discharge, increase the circumference of the morning-glory, create subatmospheric pressures under the nappe, or to use some combinations of these three methods. It was considered undesirable by the designers to increase the circumference of the morning-glory crest line since the size of the ring gate and the structure in general would need to be increased. It was considered permissible, upon the advice of the hydrologists, to reduce the maximum capacity of the structure and it was felt permissible by all concerned to make use of controlled subatmospheric pressures on the spillway face.

At a conference of engineers concerned with the project, it was decided that subatmospheric pressures up to about 10 feet of water could be tolerated. Therefore, a test was made arbitrarily using a maximum flow of 51,000 second-feet and a measured undernappe pressure of 9.3 feet of water below atmospheric. The undernappe profile from this test data is plotted in Figure 42. The throat diameter at elevation 3520 measured 37 feet and the reservoir elevation was determined to be 3562.97, almost 2 feet under the allowable maximum. Therefore, for maximum reservoir elevation of 3564.9, the capacity could either be increased above 51,000 second-feet or the subatmospheric pressure could be decreased from 9.3 feet of water or a combination of both. Since the two measured profiles described above and plotted in Figure 42 apparently bracketed the desired crest profile, the recommended profile was arbitrarily drawn as an average between the two, but drawn so as to become tangent to the fixed throat diameter of 37 feet at elevation 3520. It was now necessary to test this profile shape in the spillway model before it could be recommended for prototype construction.

To define the crest shape of the recommended profile, two equations were computed from which the X and Y coordinate points shown in Figures 25 and 6c may be obtained. The portion of the crest shape falling on the circular ring gate was defined by the equation

$$Y = 0.09494X^2$$

while the portion below the ring gate was defined by the equation

$$\log_{10}X = \log_{10}13.5 - 0.3957\ (\log_{10}28_Y)\ 1.2838$$

Of interest here, in connection with the circular weir studies, is the fact that the nappe could be made to flutter in a manner similar to that which occurred in Step 10 for the third morning-glory crest with the vent pier on the ring gate. Certain combinations of undernappe subatmospheric pressures and nappe thicknesses caused the nappe to part and allow air to enter the underside from above. Once air was admitted to the underside, the parting closed and the jet through the circular weir contracted. With the jet contracted, subatmospheric pressures under the nappe again became sufficient to expand the jet and again part the nappe. This cycle of events was repeated in rapid succession, so rapid in fact, that slow motion movies were necessary to record the action. For thick nappes with large subatmospheric pressures under them the flutter was so violent as to shake the very sturdily constructed model. This phenomenon is mentioned here to describe a condition which must be guarded against in designing a morning-glory spillway.

Twelfth Step--Recommended Morning-glory with Vent Pier on Ring Gate and an 80-square-foot Vent in Recommended Upper Bend

Description. The recommended crest obtained from the circular weir tests described above was first installed and tested using the vent system tested with the third crest. The venting system included the 80-square-foot vent in the crown of the upper bend and the vent pier on the gate crest as shown with the third crest in Figure 40a. Since the throat diameter of the recommended crest was the same as for the third crest, the size and shape of the upper bend remained unchanged and is shown as the recommended upper bend in Figure 34f.

Flow characteristics. Tests showed the structure to be capable of passing slightly more than 50,000 second-feet at maximum reservoir elevation. Surging occurred in the morning-glory entrance at approximately 1-minute intervals for flows of between 42,000 and 48,000 second-feet when the gate was seated. This surging will be discussed further in connection with the pressure tests. Zigzag flow through the tunnel was still as prominent as in the preliminary design. It was most noticeable for 30,000 to 35,000 second-feet with the gate elevated and with the reservoir at maximum elevation.

Pressures. Pressure tests showed that with the gate slightly elevated the vent pier operated satisfactorily in venting the undernappe for all flows as was evidenced by the fact that crest pressures remained very close to atmospheric. However, with the gate seated, as in Test 107 recorded in Table 4, the vent pier ventilated the undernappe satisfactorily only for flows less than 42,000 second-feet. At 42,000 second-feet the "mushroom" or center column of water in the glory hole began to surge at approximately 1-minute intervals in the model. The undernappe alternately vented and failed to vent. The jet diameter below the throat expanded and contracted accordingly. Surging was greatest with a flow of about 45,000 second-feet. For 45,000 second-feet, pressures on the spillway face between ring gate and the throat were as low as 10 feet of water below atmospheric, recorded in Test 107 and shown in Figure 43. As the flow was increased to 50,000 second-feet, it became more stable and pressures on the spillway face approached atmospheric. Some pressures rose to above atmospheric, but those piezometers immediately above, below, and under the lip of the ring gate still recorded approximately 5 feet of water below atmospheric shown in Test 107 in Figure 44a.

The surging could be eliminated by raising the ring gate one-half foot for all flows between 42,000 and 50,000 second-feet, and subatmospheric pressures on the crest could be minimized sufficiently by raising the gate 1.7 feet as shown in Figure 43. This method of eliminating the surge and reducing the subatmospheric pressure was undesirable since the reservoir water surface for a given discharge was increased. Also, it was undesirable since, in the prototype operation, there would be some risk that the operator might fail to make the gate elevation adjustment. It was considered desirable to make the operation of the spillway ring gate foolproof in this respect.

Further tests showed that the surging could also be eliminated by adding five piers to the crest outside of the ring gate circumference. The piers were similar to those shown in Figure 29b, with the exception that the downstream ends of the piers were made square to produce partings in the nappe through which air could pass to the underside. The additional air eliminated the surge but the designers did not wish to make sizable additions to the structure in the form of piers if other less conspicuous and less costly means could be found.

Conclusions. The tests indicated that the crest shape was a major improvement over the previous shapes tested, since for the maximum flow of approximately 50,000 second-feet, no severe subatmospheric pressures were recorded. Therefore, it was believed that this crest shape could be used for the recommended design if a suitable venting system could be developed. The vent pier did not perform satisfactorily for flows between 42,000 and 50,000 second-feet. However, the mechanical designers were not in favor of using the vent pier in any case because it caused an eccentric loading of the ring gate; therefore, further studies using the vent pier were abandoned. Testing was continued to determine an improved venting system.

Thirteenth Step--Recommended Morning-glory with Square-nose Control Pier and 80-square-foot Vent in Recommended Upper Bend

The vent pier in Step 12 was removed but the square nose of the control pier was retained to form an air gap in the nappe through which air could reach the underside of the nappe for elevated positions of the gate. The square nose pier, however, was not intended to vent the undernappe with the gate seated. Therefore, tests in this step were made to determine the necessity for undernappe vents with the gate seated for the recommended morning-glory crest shape.

The capacity of the morning-glory crest was 50,000 second-feet with the reservoir elevation 0.5 of a foot under elevation 3564.9. For 50,000 second-feet with the gate seated, pressures were atmospheric or above on the invert side of the morning-glory crest face, but were a little below atmospheric on the gate crest and on the crown side of the morning-glory. On the crown side of the morning-glory throat, the pressure was as much as 10 feet of water below atmospheric at Piezometer 44 as shown recorded in Test 118 and in Figure 44a.

All pressures recorded in the morning-glory for 30,000 to 45,000 second-feet with the gate seated were subatmospheric as shown recorded in Test 118 in Table 4. The subatmospheric pressures recorded were a little below atmospheric but were considered too great for these more frequent flows. As much as 7 feet of water below atmospheric was recorded at Piezometer 44 for 30,000 second-feet. For 30,000 second-feet in the previous step, where the vent pier was used to vent the undernappe, pressures along the crown and invert sides of the morning-glory throat with the gates seated were only slightly below atmospheric as shown recorded in Test 107(1) in Table 4 and only 1 foot of water below atmospheric at Piezometer 44. Therefore, venting the undernappe proved desirable. The square-nose control pier proved satisfactory in venting the undernappe with the gate elevated, but the zigzag flow through the tunnel was very prominent.

These tests indicated that the recommended morning-glory might be operated satisfactorily without undernappe venting but that undernappe venting does improve pressure conditions. It was desirable then to also determine the value of the vent in the upper bend, so the next step was to close the upper bend vent in addition to the undernappe vents.

Fourteenth Step--Recommended Morning-glory with No Ventilation of the Undernappe or Recommended Upper Bend

Pressures were recorded in Test 119, Table 4, on the crown of the upper and lower bends as well as on the invert and crown side of the morning-glory crest for discharges of 30,000, 40,000, 50,000 and 53,000 second-feet. The pressure on the crown side of the morning-glory throat was 15 feet below atmospheric for 50,000 second-feet as shown in Figure 44a and 20 feet below for 53,000 second-feet. Severe subatmospheric pressures also occurred in the crown of the upper and lower bends for these discharges.

As a result of the excessive subatmospheric pressure in the throat, negative head was sufficient to make possible a maximum discharge of a little more than 53,000 second-feet for the maximum reservoir. For 53,000 second-feet the flow throughout the tunnel surged, as indicated by the fluctuating pressure at Piezometer 68a in the crown of the lower bend, but for 50,000 second-feet and less the flow was steady.

Pressures for 30,000 and 40,000 second-feet were as much as 9 and 13 feet of water, respectively, below atmospheric at Piezometer 44 on the crown side of the morning-glory throat. The zigzag flow that occurred for 30,000 second-feet and less was much more prominent without the vent in the upper bend than it was with the vent.

It was concluded that vents are a necessary part of a structure of this type and that further tests should be made to determine the best locations and necessary sizes. Therefore, the next step was to determine whether vents under the ring gate lip could be used successfully for venting the undernappe and tunnel; and, if so, where they should be located.

Fifteenth Step--Recommended Morning-glory with Eight Individual Vents to the Undernappe but with no Vents in Recommended Upper Bend

The next step was to determine if vents under the ring gate lip could be used successfully with the recommended crest shape and to determine if these vents alone would suffice without further venting in the upper bend. Although this system of venting had failed in the preliminary design, it was believed that it could be modified to perform satisfactorily with the recommended crest shape, since Pressure Tests 107, 118, and 119, shown in Figure 44a, indicated that the region in which the vents were to be located was now subatmospheric.

The model venting system was modified somewhat from the intended prototype design. In the prototype the vents were to be manifolded together, while in the model, separate vents were to be used so that if one filled with water, all would not necessarily fill. For test purposes, this was an advantage inasmuch as it could easily be determined which locations were effective in venting the undernappe and which were not. In the model, the venting system consisted of eight 3/8-inch round openings drilled through the crest structure under the ring gate lip. The holes were spaced radially on 45° centers, beginning at the control pier. To each of the eight vent openings, copper tubes of the same inside diameter extended down through the crest and out through the reservoir. The tubes were bent up so that the free ends emerged above the surface of the reservoir about 2 feet from the crest. The square-nose pier was replaced by the preliminary design pier.

Pressure Test 120 in Table 4 showed only six of the eight vents to be effective for discharges from 30,000 to 53,000 second-feet; the vent at the control pier and the first vent clockwise filled with water for all flows. The six vents that were effective were of value in improving the pressure conditions, but the improvement was not considered adequate. Practically all pressures in this test were below atmospheric for all discharges; this was especially so for flows of 50,000 and 53,000 second-feet. For 50,000 and 53,000 second-feet the subatmospheric pressures were 12 and 17 feet of water, respectively, on the crown side of the morning-glory throat; 11 and 15, respectively, on the crown of upper bend; and 7 and 16 feet, respectively, on the crown of the lower bend. Figure 44a shows the pressures recorded in the crown and invert sides of the morning-glory crest for 50,000 second-feet.

Zigzag flow was quite prominent for flows under 35,000 second-feet, more so than when a vent was provided in the upper bend. Some surging occurred in the tunnel for both 50,000 and 53,000 second-feet.

The tests in this step showed that the vents under the gate lip are effective if not located too close to the control pier; but they alone are not enough. A vent in the crown of the upper bend is necessary to eliminate the surge, to minimize subatmospheric pressures, and to aid in straightening the flow through the tunnel. Therefore, the next step was to make tests with the vents under the gate lip along with a vent in the upper bend.

Sixteenth Step--Recommended Morning-glory with Eight Individual Vents to Undernappe and an 80-square-foot Vent in Recommended Upper Bend

From the tests thus far, it was concluded that the crown of the upper bend must be vented for satisfactory operation, and that it would also be desirable to ventilate the undernappe, if economically possible. Therefore, tests were conducted using the 80-square-foot vent in the crown of the upper bend along with the eight individual vents under the gate lip.

All pressures recorded in the morning-glory from the crest to the throat and in the crown of the upper and lower bends were atmospheric or only slightly below for all flows up to and including 50,000 second-feet recorded in Test 121 shown in Table 4. No pressure was more than 2 feet below atmospheric. Pressures recorded for 50,000 second-feet are also shown in Figure 44b. As a result of these very small subatmospheric pressures in the morning-glory throat, very little negative head was available for increasing the discharge; therefore, the discharge for maximum reservoir elevation was reduced to 50,000 second-feet, but this was ample according to the hydrologists.

For discharges of from 30,000 to 45,000 second-feet, only five of the eight vents were found to be effective in venting the undernappe since the vent at the control pier and the first ones to the right and left of the control pier filled with water. For 50,000 second-feet it was observed that only four vents were effective; one more vent counterclockwise from the control pier filled with water.

No flutter of the nappe was observed. The surging that previously existed with the vent pier did not now exist. Flow through the tunnel for the higher flows was straight and steady. The zigzag flow pattern still existed for the lower flows, however, and was most apparent for 30,000 second-feet, but was not as apparent as when no vent to the crown of the upper bend was provided.

The recommended crest shape together with the vents as installed in this step were completely satisfactory except for the four undernappe vents which filled with water. These were of no immediate concern since they could be omitted or relocated.

To determine whether or not the 80 square feet of vent in the crown of the upper bend could be reduced in the interest of economy, the size of the vent opening was varied while pressures were recorded at key piezometers in subatmospheric pressure areas throughout the spillway. Results of these tests are plotted in Figure 45. From the results it was determined that a vent area of approximately 25 square feet would be sufficient to prevent subatmospheric pressures greater than 7 feet of water at any point in the structure. The designers found it desirable to combine the upper bend air duct with the air vent duct required for the undernappe vents. Therefore, a dual purpose duct having 36 square feet of cross-sectioned area was used for the prototype extending from the right abutment to the upper bend as shown in Figures 6a, b, c, and 7.

Seventeenth Step--Recommended Morning-glory with the Recommended Venting System

Description. The recommended venting system consisted of a 6-foot-square air duct in the left abutment of the dam which supplied air to the crown of the spillway tunnel and to nine air vents located in the crest structure under the ring gate lip. The vents under the gate lip were located in the effective venting region as determined in the sixteenth step. The air venting system is shown in Figures 6a, b, c, and 7. The air duct entrance into the spillway tunnel was first designed with a bellmouth entrance. Model tests described later showed that it was better to construct the top and left-hand edges square as shown in the figures.

The air ventilation system as installed in the model is partially shown in Figure 16. Details of the prototype design which were not important to the model tests were modified slightly for more convenient model construction. The air chamber encircling the interior of the crest was modified in the model, and the four vertical bends in the prototype air duct were replaced by one 90° vertical bend. The area and location of all vent openings under the ring gate lip, the size of the air duct, and the location of its entrance into the spillway tunnel were all built to scale in the model. The length of the air duct and the one horizontal bend in the air duct were also simulated to scale in the model. The model of the recommended morning-glory showing the air duct entrance to the crown of the upper bend is shown in Figure 46a. The air duct tunnel can partially be seen in Figure 46a.

Flow characteristics. It was learned at this time that the prototype spillway is scheduled to be operated in the following manner. No water will be discharged through the spillway until reservoir elevation 3560 is reached, which will require the gate to be elevated 12 feet above its seated position. As the reservoir water surface rises above elevation 3560, the gate will be gradually lowered, in order to maintain the water surface at elevation 3560. As the gate is lowered, the discharge for reservoir elevation 3560 will increase to approximately 35,000 second-feet at which time the gate will be seated. Then, as the reservoir rises to its maximum elevation, the discharge will increase to approximately 50,000 second-feet. The model was operated and photographed with this operating procedure in mind. Flows of 15,000, 35,000, and 50,000 second-feet were photographed. These are shown in Figures 46 through 48, inclusive.

For discharges of 35,000 second-feet and under the flow still swirled and zigzagged through the tunnel due to the main portion of the flow entering the spillway at an appreciable angle to the center line of the tunnel. The designers, however, were not greatly concerned with this flow pattern since subatmospheric pressures were not now severe in the model tunnel. Pressure measurements are described later.

During the performance tests of typical prototype operating conditions it was noted that the horizontal portion of the air duct tunnel oftentimes partially filled with water; therefore, tests were made to determine the cause. With the gate elevated the flow sprang free of the crest profile except near the control pier. Here the flow in contact with the crest profile swirled downward and clockwise toward the invert of the tunnel. Some of the flow swirled completely past the invert and over the crown of the upper bend in the vicinity of the air duct entrance as shown in Figure 47a. For discharges under 30,000 second-feet the swirl was high enough on the crown side of the upper bend to follow the curved left-hand edge of the bellmouth entrance into the air duct, partially filling the air duct with water. As the discharge increased above 30,000 second-feet the swirl was too low to enter the duct; and, instead, the water in the duct emptied back into the spillway tunnel.

Although the spillway is not intended to be operated for small flows with the gate seated, tests for this condition showed the flow to cling to the crest profile for discharges up to 12,000 second-feet and to follow the curved upper edge of the bellmouth entrance into the air duct partially filling the horizontal portion of the air duct with water. When the flow reached 12,000 second-feet, the horizontal portion of the air duct was completely full of water. As the flow was increased above 12,000 second-feet the undernappe broke free of the crest profile, and, therefore, did not enter the air duct from above, but due to the clockwise swirl in the upper bend water entered the air duct from the left to keep the horizontal air duct about half full of water until the flow reached approximately 30,000 second-feet. Then the swirl occurred below the air duct opening and the water in the duct emptied back into the spillway tunnel.

Decreasing the flow gradually from maximum to zero with the gate seated, the air duct remained nearly free of water until 5,000 second-feet was reached, but became completely filled when the flow was reduced to 1,000 second-feet. The gate was raised 2 feet and the test with increasing flow repeated. This time the horizontal portion of the air duct filled completely for 4,000 second-feet and remained partially filled until 32,000 second-feet was reached.

In all cases the flow entered the air duct by following the curved surfaces of the bellmouth entrance; therefore, the curves of the bellmouth entrance were replaced in the model by square edges on all four sides, but this scheme was not entirely satisfactory either. It was found that for small spillway discharges, water passed over the opening to strike the inside of the bottom edge, splashing water into and partially filling the air duct; and for larger flows up to 30,000 second-feet the clockwise swirl approached the air duct entrance from the left, passed over the opening to strike the inside edge of the right side to splash water into the duct. Therefore, the entrance was revised again by squaring only the top and left-hand edges of the air duct entrance while the other two edges remained curved as shown in Figures 6a and b. For this arrangement tests showed the air duct to remain nearly free of water for any combination of flow and gate elevation. Water, in passing over the entrance opening, struck the [illegible]ed edge of the opposite side of the entrance to splash back into the sp[illegible] way tunnel. Since this air duct entrance design was satisfactory i[illegible] preventing flow into the air duct, it was recommended for the prototype.

Pressures. Pressures were measured at all piezometer locations shown in Figure 17. The pressures for various combinations of flow and gate elevation were recorded in Tests 140 through 146, shown in Table 5. Tests 140.1, 140.2, and 144 represent scheduled operating conditions for discharges of 15,000, 35,000, and 50,000 second-feet, respectively. Crest pressures for the maximum flow of 50,000 second-feet are also shown in Figure 44b.

Areas of greatest subatmospheric pressure were found to be on the profile of the ring gate, the crown side of the morning-glory throat, and the crown of the upper bend. However, none of the subatmospheric pressures were severe. For 50,000 second-feet the greatest subatmospheric pressures measured were 7.7 feet of water at Piezometer 35 on the gate lip on the crown side of the morning-glory, 8 feet of water at Piezometer 44 on the crown side in the morning-glory throat, and 7.5 feet of water at Piezometer 57 on the crown of the upper bend. For 43,000 second-feet, 8.3 feet of water at Piezometer 35 was measured when the gate was elevated 2 feet. The latter condition, however, is not a scheduled operating condition.

The subatmospheric pressure area which occurred in the crown of the upper bend substantiated an earlier conclusion that this area was the best location for the vent to the spillway tunnel. Similarly, Piezometers 202 through 208, all located under the gate lip, substantiated the fact that the region under the gate lip, unless too near to the control pier, was well suited for the vent locations. The pressures recorded at these piezometers were subatmospheric for all combinations of discharge and gate elevation tested, as shown in Table 5.

Pressures in the air duct were also atmospheric or below for all combinations of discharge and gate elevation as shown in Table 5 by Piezometers 209, 211, and 212, indicating air flow in the duct. For flows of 30,000 to 50,000 second-feet, air flow through the model air duct was sufficient to produce a roar as well as a noticeable suction at its intake end.

The possibility of eliminating the air vents under the lip of the ring gate was investigated by closing all such vents. With these vents closed, pressures were measured at the piezometers throughout the structure for several combinations of discharge and gate elevation as shown in Tests 147 through 151, recorded in Table 5. Pressures throughout the entire structure for all flows were more subatmospheric than before. The greatest increase in subatmospheric pressure occurred at Piezometer 35 when the flow was 45,260 second-feet and the gate elevated 2 feet. The subatmospheric pressure at this point was 14.8 feet of water, while with the vents under gate lip open, it was approximately 8.3 feet. Also, Piezometers 202 and 208 located under the gate lip indicated subatmospheric pressures up to 14 feet of water, while with the vents open, the pressures here were no more than 4 feet of water below atmospheric. Thus, the vents under the ring gate lip were shown to be useful and necessary.

The possibility of the 36-square-foot air duct being closed temporarily or unavoidably during operation was investigated. This model arrangement was the same as tested in Step 14 except that the vents under gate lip in this test were interconnected with the vent in the upper bend so that it was possible for air to flow from the upper bend vent to the under gate vents or vice versa. None of the vents were free to draw air from the atmosphere since the air supply duct was closed. As a result, subatmospheric pressures of considerable degree were encountered throughout the structure as shown by Tests 152 through 156, recorded in Table 5.

As a result of the air supply duct being closed, the capacity of the morning-glory was increased to approximately 52,000 second-feet, but for this discharge several severe subatmospheric pressures existed throughout the structure. The most severe was 24 feet of water at Piezometer 57 in the crown of the upper bend. Other low pressures occurred on the crown side of the morning-glory throat, on the gate crest, under the gate lip, and in the air intake tunnel. This investigation of pressures proved the value and necessity of the entire air venting system. It is therefore recommended for prototype construction.

Forces acting on ring gate. Several tests were performed to aid the mechanical designers in the design of the ring gate. Pressures were measured on the vertical face of the outside periphery of the ring gate with the gate elevated 4, 8, and 12 feet, to determine whether unbalanced radial forces were acting on the gate. With the gate elevated 4 feet and the reservoir at maximum elevation, piezometric pressures on the side of the gate near the control pier measured about 8 to 9 percent greater than at other points on the opposite side of the morning-glory, as shown in Figure 49. This was due to the higher water surface adjacent to the control pier. Pressure fluctuations indicated in Figure 49 were caused by instability in the unsymmetrical flow entering the morning-glory. With the gate elevated to the 8- and 12-foot positions the pressure distribution around the ring gate became more equally distributed, as indicated in Figure 49, because the head on the gate was reduced from 12.9 to 8.9 and 4.9 feet, respectively.

Pressures on top of and under the ring gate crest were also measured for use by the designers, in determining the pressure differential across and under the crest portion of the ring gate at various locations around its circumference. The data from these tests are shown in Figure 50.

Calibration. For purposes of operating the ring gate to control the flow in the prototype structure and to be certain of the discharge characteristics of the morning-glory, the model spillway was calibrated. From the calibration tests, spillway discharge curves were determined for the ring gate elevated 2, 4, 6, 8, 10, and 12 feet, as well as with the ring gate seated as shown in Figure 51. Discharges for other combinations of reservoir and gate elevation can be interpolated from these curves.

The discharge coefficient "C" was computed from the free discharge equation:

$$Q = CLH^{3/2}$$

where Q is the total discharge, C is the discharge coefficient, L is the circumference of the crest line or high point of gate, and H is the head measured by the difference in elevation between the reservoir water surface and the crest line. Coefficient curves showing "C" versus "H" are shown in Figure 51 for several gate elevations.

With the gate seated, the maximum coefficient of 3.80 occurred when the discharge was about 26,000 second-feet with a head of approximately 10.5 feet. As the gate was elevated the coefficient increased for a given head. For example, with the gate elevated 2 feet, the coefficient was about 3.85 for a 10.5-foot head.

The capacity of the spillway for the maximum reservoir elevation was determined to be 49,400 second-feet, which was sufficiently close to the preliminary design flow of 53,000 second-feet and above the revised requirement specified by the hydrologists. The capacity of the structure as given above was considered by all concerned to be adequate.

Water surface profiles. Water surface profiles of flow over the morning-glory on the center line of tunnel were measured for a matter of record and for future use in the design of morning-glory spillways. Profiles for five discharges between 15,000 and 50,000 second-feet are shown in Figure 52.

Eighteenth Step--The Zigzag Flow Problem

One problem concerning flow conditions in the spillway remained to be solved if possible. Unsymmetrical flow in the spillway and tunnel, which has been referred to in the report as zigzag flow still existed, particularly for flows of less than 35,000 second-feet. Although the designers did not feel that the zigzag flow presented unusual flow conditions, the laboratory felt that such a flow pattern might require more tunnel ventilation in the prototype than was indicated in the model, since the sheet of water which swirled around the inside of the upper bend and over the air duct opening would entrain air to cause bulking of the flow which might obstruct the vent more than anticipated. Also, bulking of the flow due to entrained air would fill the upper bend and inclined tunnel more than indicated in the model which might result in greater subatmospheric pressures as well as possible choking and surging in the morning-glory and throughout the structure. Consequently, it was felt necessary, in the laboratory, to eliminate the zigzag flow if economically possible.

Deflector schemes. Various deflector schemes were tested. The first scheme tested was a deflector installed on the spillway face and extending downward to the throat of the morning-glory on the crown side, as shown in Figure 53. The deflector was of little benefit for flows up to 35,000 second-feet because the undernappe in the vicinity of the deflector was clear of the spillway face and the deflector was not fully utilized. The deflector also reduced the flow to less than 45,000 second-feet for maximum reservoir.

The deflector was moved to a position directly in front of the control pier but at the same elevation as before. This arrangement showed some merit for straightening the flow through the tunnel, but the capacity of the spillway still remained less than 45,000 second-feet. Since the capacity of the spillway was greatly reduced the deflector idea was abandoned.

Guide vane schemes. A set of three guide vanes had previously been tested in the second upper bend design and found to be quite successful as shown in Figure 39 and discussed in Step 9. The same idea was used again. The guide vanes were arranged as before, one on the invert of the upper bend, and the other two located 120° on either side of the invert. The model vanes were made of 1/4-inch plastic to represent concrete walls in the prototype. The vanes were 4-1/2 feet high projecting inward at right angles to the tunnel walls. The three vanes extended from elevation 3528 in the throat through the upper bend and for about 16 feet into the straight inclined portion of the tunnel. The two vanes to the right and left of the invert were 67-1/2 feet long while the one on the invert was 85-1/2 feet long. The upstream ends of the vanes were shaped to give a streamlined effect.

Performance tests showed that the vanes reduced the zigzag flow, but it was apparent that greater improvement could be obtained with longer vanes. Therefore, the length of the two vanes to the right and left of the invert was increased 54 feet; as a result, the performance was improved. However, it was noted that the vane to the right of the invert might possibly be eliminated without sacrificing good performance because only a very small quantity of the flow swirled in the counterclockwise direction. A performance test with the right vane removed showed the performance to still be satisfactory.

The effectiveness of the vane on the invert in straightening the flow was also determined by removing it from the model. Tests showed that the one left-hand vane was not sufficient by itself, but that one vane might suffice if it was relocated closer to the invert and extended in length. The vane to the left of the invert was relocated 90° to the left of the invert, instead of at the original 120°, and the vane was extended 16 feet further into the incline; no other vanes were used. Performance tests showed this arrangement to be nearly as efficient as anything yet tested for straightening the flow through the tunnel. It was not completely satisfactory, however, since it is impossible for one guide vane to be placed just right to straighten the flow for all operating discharges.

Pressures on the guide vane were measured by piezometers located as shown in Figure 54. The greatest subatmospheric pressure found was 11.5 feet of water on the edge of the vane at Piezometer 233 which occurred when the flow was 15,000 second-feet with the gate elevated to produce maximum reservoir elevation. All pressures on the vane became atmospheric or above as the flow was increased to 35,000 and 50,000 second-feet with the gate either seated or elevated.

Further tests showed that for low flows of about 5,000 to 10,000 second-feet with the gate seated, the flow alternately zigzagged and straightened. The cause was traced to a pulsating flow condition that occurred in the throat as a result of the guide vane penetrating the thin nappe of the flow that adhered to the spillway face. The guide vane opened a gap in the nappe through which air entered to relieve the subatmospheric pressures under the nappe.

As the undernappe pressures were relieved, the nappe sprang free from the spillway face. Once the nappe was free of spillway face, the 4.5-foot-high guide vane was not high enough to penetrate the nappe; therefore, a demand for air under the nappe developed again. As a result the nappe retracted to the throat walls and the process repeated. Tripling the number of vents under the gate lip was of no help in relieving the pulsating flow condition because, for these low discharges, there was practically no demand for air in the region of the vents under the gate lip, even with the undernappe in contact with the spillway face.

Guide vane plus crest pier scheme. In addition to the one guide vane used in the preceding scheme, a spillway pier located immediately counterclockwise from the crown of the tunnel was added to the crest and tested. Model performance with this scheme is shown in Figures 55, 56, and 57 for flows of 15,000, 35,000, and 50,000 second-feet.

The pier was 4-1/2 feet thick at its outward edge, had parallel edges for a distance of 3 feet toward the center of the glory hole, then tapered to a 6-inch width at its inside edge. Top of pier was the same elevation as top of control pier. It was 66 feet high from top to bottom and extended downward to below the air duct entrance. The pier was 14 feet long in plan with the outer edge located just inside the ring gate lip.

Tests showed this arrangement to perform much better than the recommended spillway with no flow-straightening device as shown by comparing Figures 47 and 48 with Figures 56 and 57. The pulsating flow that occurred in the throat for small flows, when the guide vane alone was used, was now completely eliminated because the pier opened a gap in the nappe to allow constant ventilation of the undernappe in the region of the throat, as shown in Figures 55b and 55c. Tests were conducted using the pier and a shorter guide vane, but a shorter vane was found to be not nearly so successful in straightening the flow.

Calibration tests showed the maximum capacity of the morning-glory to be about 1,500 second-feet less with the pier on the spillway, but up to 40,000 second-feet, the spillway capacity curve was identical with or without the pier. Crest pressures were changed very little by adding the pier. Pressures on the guide vane were also about the same as without the pier but were not quite as much below atmospheric.

In view of the added cost of this arrangement and the unsightly appearance of the pier structure, the designers chose not to adopt the pier and guide vane arrangement for use in the prototype structure at this time. Instead, they reasoned that should the zigzag flow pattern be found to be objectionable in the prototype, the pier and vane arrangement could be added if the need arose at practically the same cost as would be required to include it in the construction drawings. The reduced capacity of the spillway and the subatmospheric pressures on the guide vane were further reasons for not adopting the arrangement for prototype use.

Flow Conditions in the Downstream Area

The jet from the spillway portal deflector was studied, as well as erosion and flow characteristics in the river channel. The prototype spillway portal deflector and the topography of the river channel are shown in Figure 3. The model of this deflector and surrounding region was constructed as shown in Figure 8. A model view of the river channel area with the deflector in operation is shown in Figure 9a. The model of the river channel area was later revised to include the outlets, powerhouse, transmission lines, and a greater length of channel, as shown in Figures 10 and 11 to make a more complete study of the flow characteristics in the area.

The Spillway Jet

The dimensions of the jet leaving the deflector were measured for flows of 10,000, 20,000, 35,000, and 50,000 second-feet and are shown in Figure 58. It was believed that these measurements would be useful in future studies on jets, and would also provide data for model prototype comparisons at a later date.

The jet measurements showed the water surface at the end of the deflector to be at a higher elevation on the left-hand side of the deflector than on the right, as shown by elevations "g" and "h" in Figure 58. The zigzag flow pattern through the tunnel was responsible for this condition; at this point on the deflector the flow had zigzagged to the left of the tunnel center line. However, the model tunnel had been shortened 180.51 feet to obtain velocity similarity; therefore, the extra tunnel length in prototype would most likely be sufficient for the flow to return to the right-hand side of the tunnel center line by the time it reached the end of the deflector. Thus, the water surface at the end of the deflector will probably be higher on the right-hand side in the prototype. This condition is pointed out here merely for prototype comparison purposes.

The minimum flow required in the tunnel to cause the flow to spring free of the deflector was determined. Test results showed that beginning with a very small discharge, less than 1,000 second-feet, a hydraulic jump formed in the tunnel, and that it required a discharge of 3,640 second-feet to sweep the jump out and cause the deflector to function. When reducing the discharge, the flow did not fall back into the tunnel to form a jump until the discharge was 1,090 second-feet. Probably these discharges are greater than the corresponding ones for the prototype because the velocity of the flow at the outlet portal was not corrected for low flows in the model. The correction in tunnel length, described in the description of the preliminary morning-glory spillway, was to provide velocity similitude for 53,000 second-feet.

Erosion

Before erosion testing began the model river channel was lengthened and prepared as shown in Figure 59a. The river banks of the model were formed with concrete since the prototype channel was believed to be for the most part in a solid rock canyon. The river bed was formed of pea gravel in the model to provide a movable bed that could be used to indicate erosion trends.

Erosion tests were made with spillway flows of 10,000, 20,000, 35,000, and 50,000 second-feet. The tail-water elevation for each discharge was determined from the tail-water curve in Figure 3. The corresponding tail-water elevation in the model was set by regulating the tail-water gate to obtain the proper reading on the staff gage near the tail-water gate, shown in Figure 10. Each flow was run for 30 minutes in the model before increasing the discharge. The river bed was not reshaped to the original bed contour after each run; but instead, the erosion was allowed to accumulate. The depth of scour and the height of the bar which formed downstream from the scour was recorded after each discharge as shown in Figure 58. The test in progress for a flow of 50,000 second-feet is shown in Figures 59b and c. The river bed after the final run of 50,000 second-feet is shown in Figure 59d.

Further erosion tests were conducted using an anticipated sequence of events which might occur in the prototype. It was believed that if a large flood in the prototype caused erosion in the river bed and if the eroded material formed a bar in the channel, then the bar would be removed manually at the conclusion of the flood in order to lower the tail water to normal elevation to prevent loss of power head. The next flood would then occur with the river bed already eroded and with the bar removed. This sequence was simulated in a model test. First a flood of 35,000 second-feet was discharged through the spillway for 30 minutes, after which time the flow was stopped and the bar deposit removed. A flood of 35,000 was again discharged through the spillway for 30 minutes. The results of this test showed that the scour pattern was not only slightly deeper after the second run but that the scour pattern extended considerably farther downstream.

In none of the tests was erosion detected anywhere near the spillway deflector structure itself. Because of this fact and because it was believed that the bedrock of the prototype river channel would resist erosion tendencies very well, the deflector bucket of the outlet portal, as preliminarily designed, was recommended for use in the prototype.

Flow Characteristics

To make a more complete study of flow characteristics in the river channel, the outlets, the powerhouse, the transmission lines, and a concrete river bed were added to the model as shown in Figures 10 and 11. Several operating combinations of discharge from the spillway, outlets, and powerhouse were photographed in the model, some of which are shown in Figures 11b, 60a, and 60b. Tests showed that the spillway and outlet jets acted as ejectors to reduce the tail-water elevation upstream from the jets in the power plant tailrace and to raise the water surface to a higher than normal elevation downstream from the jets. The difference in elevation between these two water surfaces is plotted in Figure 61 for several operating combinations. For large spillway and outlet discharges, tests showed that a small dam across the tailrace channel as shown in Figure 11 should be provided in order to be sure that the proper minimum head on the draft tubes of the power plant would be maintained.

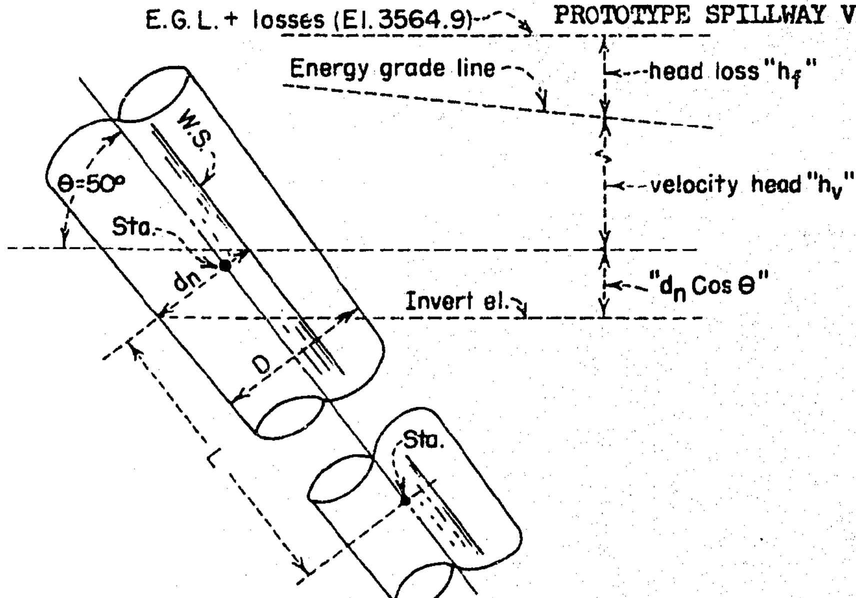
Further tests on the flow characteristics in the river channel showed the preliminary location of the power transmission lines from the powerhouse to the switchyard to be undesirable. One set of three lines sagged low near the highest portion of the spillway jet and close to the outlet jets as shown in Figure 62a. In the model these lines became very wet as a result of spray from the jets. In the prototype the lines would be subjected to much greater proportions of spray because the model was not capable of duplicating the prototype spray to scale. In the colder months, perhaps, the lines might snap if water on the lines should freeze; therefore, it was recommended that the lines be relocated. The designers relocated the lines farther upstream and used only one transmission tower as shown in Figure 62b. This turned out to be an economical move as well as a much dryer location with reference to the spillway and outlet jets.

Operation of the model with the spillway and outlet jets discharging showed a considerable amount of splash and wave action to also occur on the banks of the river channel. Therefore, the designers recommended that the banks be riprapped or protected in some way near the switchyard and along the access road to the switchyard. It was also recommended that the manhole covers on a conduit leading from the powerhouse to the switchyard be raised several feet to prevent splash water from draining into the conduit. The conduit carried switchyard control cables and is shown in Figures 2 and 3.

Interior - Reclamation - Denver, Colo.

Table 1

PROTOTYPE SPILLWAY VELOCITY COMPUTATIONS



DATA

1 Max. W.S. el. 3564.9
2 Max. Q 53,000 cfs
3 Designed neg. head at throat 6.4'
4 Computed upper bend loss 8'
5 Head loss at lower bend assumed to be zero
6 Head losses to throat (el. 3523.0) assumed to be zero
7 Roughness coefficient "n" estimated to be 0.14

FORMULAS

$$V = \frac{Q}{A}; \quad h_v = \frac{V^2}{2g}; \quad s = \frac{n^2 V^2}{2.2082 r^{4/3}}; \quad h_f = sL$$

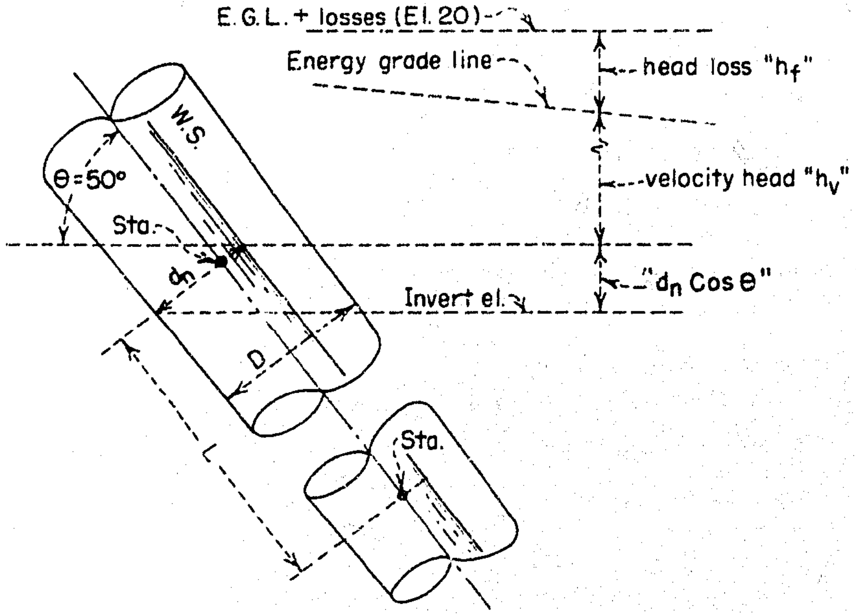
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
℄ Sta.	℄ el.	Invert el.	D	$\frac{d_n}{D}$	d_n	d_nCosθ	A	V	h_v	r	s	Avg. s	L	h_f	$\sum h_f$	d_nCosθ +h_v+h_f	E.G.L.+ losses el.
5+07.00	3523.00		34.79	1.00	--	--	950.6	55.75	48.3	8.70	0.0154	--					
5+25.25	3469.86		34.79	0.72	25.05	16.10	732.7	72.30	81.2	10.38	.0205	0.0180	57.45	1.03	9.03	106.33	3565.0
6+20.64	3356.18		31.36	0.59	18.50	11.89	474.2	111.8	194.1	8.63	.0627	.0416	148.4	6.17	15.20	221.2	3567.3
7+16.03	3242.50		27.93	0.60	16.76	10.77	383.8	138.1	296.1	7.75	.1105	.0866	148.4	12.85	28.05	334.9	3568.4
8+11.41	3128.83		24.50	0.67	16.42	10.55	335.8	157.8	386.7	7.15	.1606	.1356	148.4	20.12	48.17	445.4	3566.4
8+73.08	--	3073.50	24.50	0.65	15.92	--	324.4	163.4	414.6	7.06	.1750	.1678	78.5	13.17	61.34	491.9	3565.4
9+97.84	--	3073.24	24.50	~~0.68~~	~~16.66~~	~~--~~	~~341.4~~	~~155.2~~	~~374.0~~	~~7.19~~	~~.1542~~	~~.1646~~	~~124.8~~	~~20.54~~	~~81.88~~	~~472.5~~	~~3545.8~~ *
				0.67	16.42	--	335.8	157.8	386.7	7.15	.1606	.1678		20.94	82.28	485.4	3558.6
11+22.59	--	3073.03	24.50	~~0.69~~	~~16.90~~	~~--~~	~~346.9~~	~~152.8~~	~~362.5~~	~~7.23~~	~~.1484~~	~~.1545~~	~~124.8~~	~~19.28~~	~~101.56~~	~~481.0~~	~~3554.0~~ *
				0.68	16.66	--	341.4	155.2	374.0	7.19	.1542	.1574		19.64	101.92	492.6	3565.6
12+88.59	--	3072.72	31.00	0.43	13.33	--	352.4	150.4	351.2	7.30	.1419	.1480	166.0	24.57	126.49	491.0	3563.7
14+02.09	--	3072.50	31.00	0.44	13.64	--	362.0	146.4	332.8	7.41	.1317	.1368	113.5	15.53	142.02	488.5	3561.0

Column 5 assumed.
Column 17 equals depth plus velocity head plus losses.
Column 18 equals invert elevation plus Column 17.

*The assumed value of d_n in Column 5 is not close enough to true value.

Table 2

1:36 MODEL SPILLWAY VELOCITY COMPUTATIONS



DATA

1 Prototype max. W.S. el. 3564.9 = model el. 20.0'
2 Prototype Q of 53,000 cfs = model Q of 6.816 cfs
3 Designed neg. head at throat of 6.4' proto. = 0.18' model
4 Computed upper bend head loss of 8' proto. = 0.222' model
5 Head loss at lower bend assumed to be zero
6 Head losses to throat (model el. 18.836) assumed to be zero
7 Roughness coefficient "n" estimated to be 0.10

FORMULAS

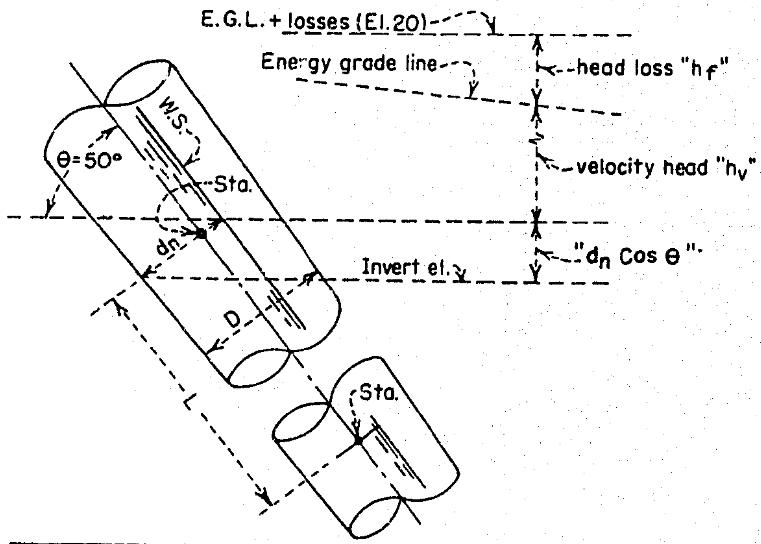
$$V = \frac{Q}{A}; \quad h_v = \frac{V^2}{2g}; \quad s = \frac{n^2 V^2}{2.2082 r^{4/3}}; \quad h_f = sL$$

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
℄ Sta.	℄ el.	Invert el.	D	$\frac{d_n}{D}$	d_n	$d_n \cos\theta$	A	V	h_v	r	s	Avg. s	L	h_f	Σh_f	$d_n\cos\theta + h_v + h_f$	E.G.L. + losses el.
5+07.00	18.836	--	0.966	1.00	--	--	0.733	9.29	1.340	0.242	0.0260					1.16	20.00
5+25.25	17.360	17.049	.966	0.72	0.696	0.447	.565	12.06	2.258	.288	.0346	0.0303	1.60	0.048	0.270	2.975	20.024
6+20.64		13.922	.871	0.60	.523	.336	.373	18.27	5.183	.242	.1004	.0675	4.12	.278	0.548	6.067	19.989
7+16.03		10.795	.776	0.61	.473	.304	.302	22.57	7.910	.217	.1771	.1388	4.12	.572	1.120	9.334	20.129
8+11.41		7.668	.681	0.69	.470	.302	.268	25.43	10.042	.201	.2487	.2129	4.12	.877	1.997	12.341	20.009
8+73.08		6.350	.681	0.67	.456	--	.259	26.32	10.757	.199	.2700	.2594	2.18	.565	2.562	13.775	20.125
9+97.84		6.343	.681	0.70	.477		.272	25.06	9.752	.202	.2404	.2552	3.47	.886	3.448	13.677	20.020
11+22.59		6.337	.681	0.73	.497		.285	23.92	8.885	.204	.2164	.2284	3.47	.792	4.240	13.622	19.959
12+88.59		6.328	.861	0.46	.396		.294	23.18	8.343	.211	.1939	.2049	4.61	.945	5.185	13.924	20.252
				0.47	.405		.301	22.64	7.959	.214	.1821	.1992		.914	5.158	13.522	19.840
14+02.09		6.322	.861	0.48	.413		.309	22.06	7.557	.216	.1702	.1759	3.15	.554	5.712	13.682	20.004

Column 5 assumed.
Column 17 equals depth plus velocity head plus losses.
Column 18 equals invert elevation plus Column 17.

Table 3

1:36 MODEL SPILLWAY VELOCITY COMPUTATIONS
(249.51' of 24.5' diameter conduit downstream from lower bend is shortened to 23" in the model)



DATA

1 Prototype max.W.S. el.3564.9 = model el.20.0'
2 Prototype Q of 53,000 cfs = model Q of 6.816 cfs
3 Designed neg. head at throat of 6.4' proto.=0.18' model
4 Computed upper bend head loss of 8' proto.=0.222' model
5 Head loss at lower bend assumed to be zero
6 Head losses to throat (model el.18.836) assumed to be zero
7 Roughness coefficient "n" estimated to be 0.10

FORMULAS

$$V = \frac{Q}{A};\quad h_v = \frac{V^2}{2g};\quad s = \frac{n^2V^2}{2.2082r^{4/3}};\quad h_f = sL$$

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
℄ Sta.	℄ el.	Invert el.	D	$\frac{d_n}{D}$	d_n	d_nCosθ	A	V	h_v	r	s	Avg. s	L	h_f	Σh_f	d_nCosθ $+h_v+h_f$	E.G.L.+ losses el.
5+07.00	18.836		0.966	1.00			0.733	9.29	1.340	0.242	0.0260					1.16	20.00
5+25.25	17.360	17.049	.966	0.72	0.696	0.447	.565	12.06	2.258	.288	.0346	0.0303	1.60	0.048	0.270	2.975	20.024
6+20.64		13.922	.871	0.60	.523	.336	.373	18.27	5.183	.242	.1004	.0675	4.12	0.278	0.548	6.067	19.989
7+16.03		10.795	.776	0.61	.473	.304	.302	22.57	7.910	.217	.1771	.1388	4.12	0.572	1.120	9.334	20.129
8+11.41		7.668	.681	0.69	.470	.302	.268	25.43	10.042	.201	.2487	.2129	4.12	0.877	1.997	12.341	20.009
8+73.08		6.350	.681	0.67	.456		.259	26.32	10.757	.199	.2700	.2594	2.18	0.565	2.562	13.775	20.125
9+42.08		6.346	.681	0.69	.470		.2681	25.423	10.036	.201	.2500	.2600	1.92	0.498	3.060	13.566	19.912
11+08.08		6.337	.861	0.44	.379		.2793	24.404	9.248	.206	.2222	.2361	4.61	1.088	4.148	13.775	20.112
12+21.58		6.331	.861	0.46	.396		.2940	23.184	8.346	.211	.1936	.2079	3.15	0.655	4.803	13.545	19.876

Column 5 assumed.
Column 17 equals depth plus velocity head plus losses.
Column 18 equals invert elevation plus Column 17.

TABLE 4 PRESSURES RECORDED FOR THE SPILLWAY MODEL

Test No.	Step No.	Model arrangement	Remarks	Discharge cfs.	Gate crest el. ft.	Res. el. ft.
15&17		Preliminary design	Vents under gate lip did not function. Pressure on crown of incline fluctuated from zero to values shown	53,000	3548.0	3564.9
22		do	Vents under gate lip did not function	40,000	do	3561.8
26		do	do	35,000	do	3560.6
5		do	do	30,000	do	3559.4
6		do	do	10,000	do	3553.8
12&19		do	Vents under gate lip functioned except those near control pier	40,000	3550.9	3564.9
24		do	do	35,000	3552.3	do
11&18		do	do	30,000	3553.0	do
4	1	Preliminary design with radial piers on crest	Vents under gate lip did not function	53,000	3548.0	do
10&16	2	Preliminary design with one 2.6-foot-diameter vent in upper bend near el 3520	Vents under gate lip did not function. Pressures on crown of incline fluctuated to maximums shown	53,000	do	3565.9
21	2	do	Vents under gate lip did not function	40,000	do	3562.0
23	2	do	do	30,000	do	3559.4
28	3	Preliminary design with three 2.6-foot-diameter vents in upper bend near el 3520	do	53,000	3548.0	3566.1
38	4	Preliminary design with six 2.6-foot-diameter vents in upper bend near el 3520	do	53,000	do	3567.8
40	5	Preliminary design with six 2.6-foot-diameter vents in upper bend and radial piers outside of ring gate	do	do	do	3565.7
45	6	Preliminary crest without a tunnel	do	do	do	3568.0
53	8	Same as Test No. 40 except with entire length of 24.5-foot-diameter circular tunnel downstream from preliminary lower bend	do	do	do	do
59	8	Same as Test No. 40 except with recommended lower bend and entire length of 24.5-foot-diameter circular tunnel downstream	do	do	do	do
84	9	Second crest with the tunnel removed	Undernappe was not ventilated	53,000	do	3563.1
82	9	do	do	35,000	do	3595.5
85	9	Second crest with square nose pier and no tunnel	do	53,000	do	3564.0
83	9	do	do	35,000	do	3559.9
103(1)	10	Third crest with pier vent and 80 square foot vent in upper bend*	Pier vent failed to ventilate the undernappe	53,000	do	3565.7
105(1)	10	do	Undernappe was ventilated	40,000	3551.6	3564.9
107(1)	12	Recommended crest with vents as in Test 103*	do	30,000	3548.0	3559.2
107(3)	12	do	do	40,000	do	3561.9
107(4)	12	do	Undernappe was alternately ventilated and not ventilated	45,000	do	3563.0
107(5)	12	do	Undernappe was not ventilated	50,000	do	3564.6
109(1)	12	do	Undernappe was ventilated	45,000	3549.7	3564.8
112(1)	12	do	do	45,000	3548.5	3563.6
115(1)	13	Recommended crest with square nose control pier with 80 square foot vent in upper bend*	Undernappe was not ventilated	30,000	3548.0	3559.2
118(3)	13	do	do	40,000	do	3561.5
118(4)	13	do	do	45,000	do	3562.7
118(5)	13	do	do	50,000	do	3564.4
119(1)	14	Recommended crest with no air vents*	do	30,000	do	3559.2
119(3)	14	do	do	40,000	do	3561.5
119(4)	14	do	do	50,000	do	3564.0
119(5)	14	do	do	53,000	do	3564.7
120(1)	15	Recommended crest with 8 vents 1 square foot each under gate lip, with no vent in upper bend*	Two vents near control pier not effective	30,000	do	3559.2
120(2)	15	do	do	40,000	do	3561.6
120(3)	15	do	do	50,000	do	3564.1
120(4)	15	do	do	53,000	do	3564.8
121(1)	16	Recommended crest with 8 vents 1 square foot each under gate lip with 80 square foot vent in upper bend*	Three vents nearest control pier not effective	30,000	do	3559.4
121(2)	16	do	do	40,000	do	3561.9
121(3)	16	do	do	45,000	do	3563.4
121(4)	16	do	Four vents near control pier not effective	50,000	do	3565.0

Morning-glory pressures **

Test No.	Piezometers 90 degrees to left of tunnel center line									Piezometers on invert side of morning-glory along center line of tunnel												
	In gate crest				In spillway face					In gate crest				In spillway face								
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
15&17	-5	-15	-17	-8	-4	--5	-9	-21	-23	+1	-7	-10	-4	+1	-1	-3	-7	-13	-19	-25	-27	-22
22	-1	-9	-12	-6	-3	-3	-5	-5	-3	+2	-4	-7	-3	+1	+0	-1	-3	-5	-8	-10	-10	-6
26	+2	-9	-10	-8	-3	-3	--8	-6	-1	+2	-3	-6	-3	+1	0	-1	-3	-4	-7	-8	-8	-3
5	+1	-5	-8	-4	0	-3	-7	-10	-6	-2	-4	-5	-3	+1	0	-1	-3	-4	-6	-8	-7	-4
6	+3	0	--1	0	+1	0	-2	-3	-2	+3	0	-1	0	+1	+1	0	-1	-1	-2	-3	-3	-2
12&19	-5	-11	-12	-4	-4	-4	-4	-4	-3	-2	-7	-9	-5	-3	-2	+6	+2	-3	-7	-10	-10	-5
24	-5	-9	-10	-5	-3	-3	-3	-4	-4	-3	-5	-8	-4	-3	-3	-1	+3	+1	-6	-10	-10	-5
11&18	-4	-3	-5	0	-3	-3	-3	-3	-3	-3	-4	-7	-3	-3	-2	0	+5	+1	-4	-8	-9	-5
4	-14	-6	-14	-8	-4	-6	-15	-25	-26	-16	-10	-12	-12	-6	-4	-4	-8	-12	-18	-23	-25	-21
10&16	-3	-13	-11	-6	-1	-3	-13	-27	-26	+3	-4	-6	-1	+4	+3	+1	-4	-9	-19	-25	-27	-22
21	-1	-9	-12	-6	-2	-3	-4	-4	-1	+2	-4	-7	-3	+1	+1	0	-3	-5	-8	-9	-9	-9
23	+1	-5	-8	-4	0	-3	-7	-9	-3	+3	-3	-5	-2	+1	0	0	-3	-4	-6	-7	-7	-3
28	-1	-10	-11	-3	+3	-1	-10	-21	-19	+6	+1	-2	+4	+9	+8	+7	+3	-3	-9	-15	-16	-11
38	+1	-7	-8	0	+4	+2	-8	-17	-13	+11	+6	+4	+7	+13	+11	+9	+5	0	-7	-12	-13	-7
40	+3	-5	-6	0	+5	+3	-7	-16	-13	+7	+1	0	+4	+8	+7	+5	+1	-4	-9	-14	-14	-9
45	+2	-6	-7	0	+5	+3	-7	-16		+9	+6	+4	+8	+13	+11	+9	+4	0	-8	-14	-16	-11
53																						
59																						
84										-4	+1	-4	-8			-2		-2		0		
82										+1	+2	+1	-4			0		-1		0		
85										-1	+3	+1	+1			+1	-	0		0		
83										-2	+4	+1	+1			0		0		0		
103(1)										+3	-4	-5	+2	+5	+5	+3	-1	-9	-11	-14	-2	+5
105(1)										-3	-7	-8	-3	-1	0	-1	-1	-1	-1	-1	-1	-1
107(1)										+5	0		-2	-1	-1	-1	-1	-1	-1	-1	-1	-1
107(3)										+5	-1		-2	-2	-2	-2	-2	-2	-2	-1	-1	-1
107(4)										+4	-4		-7	-9	-7	-6	-5	-4	-2	-1	0	+1
107(5)										+5	-2		-3	-3	+2	+2	+3	+4	+4	+5	+4	+4
109(1)										+1	-4		-3	-2	-1	-1	-1	-1	-1	+1	+1	+2
112(1)										+2	-3		-4	-5	-6	-5	-4	-1	0	+3	+1	+1
115(1)										+4	-1		-4	-5	-4	-4	-4	-3	-3	-2	-3	-5
118(3)										+4	-3		-6	-7	-5	-5	-5	-4	-4	-3	-4	-5
118(4)										+3	-4		-7	-8	-6	-5	-5	-4	-3	-2	-3	-3
118(5)										+5	-3		-4	-3	0	+2	+2	+3	+3	+3	+2	+2
119(1)										+4	-1		-4	-5	-4	-4	-4	-3	-2	-2	-3	-5
119(3)										+4	-3		-6	-7	-6	-5	-5	-4	-4	-3	-4	-5
119(4)										+3	-5		-7	-7	-5	-4	-4	-3	-2	-1	-2	-3
119(5)										+3	-5		-7	-7	-5	-3	-3	-3	-3	-3	-4	-5
120(1)										+5	-1		-2	-3	-2	-3	-2	-3	-2	-2	-2	-2
120(2)										+4	--2		-4	-5	-4	-4	-5	-4	-4	-4	-4	-4
120(3)										+4	-4		-6	-7	-4	-4	-3	-3	-3	-3	-4	-3
120(4)										+4	-5		-6	-8	-6	-4	-5	-4	-4	-4	-6	-5
121(1)										+5	0		-2	-2	-1	-2	-1	-1	-1	-1	-1	-1
121(2)										+5	-2		-2	-2	-2	-2	-1	-1	-1	-1	-1	-1
121(3)										+5	-2		-2	-2	-2	-2	-1	+1	+2	+2	+1	0
121(4)										+6	-1		-1	--1	+2	+3	+3	-1	+3	+3	+2	+2

Test No.	Piezometers along center line of control pier to the right of tunnel center line									Piezometers on crown side of morning-glory along center line of tunnel													Piezometers near vents under gate	
	In gate crest				In spillway face					In gate crest				In spillway face										
	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46
15&17	+13	+10	+7	+8	+10	+7	-4	-20	-21	-2	-11	-14	-6	-3	-4	-6	-10	-18	-25	-30	-32	-32	-1	-5
22	+13	+9	+5	+6	+8	+7	+1	-7	-5	0	-7	-10	-5	-1	-2	-3	-6	-9	-12	-14	-14	-13	+1	-3
26	+10	+7	+3	+3	+7	+6	-1	-5	-4	+1	-6	-8	-4	-1	-1	-3	-5	-9	-11	-13	-13	-12	-1	-2
5		+6	+2	+3	+5	+4	0	-5	-3	+1	-4	∓7	-3	0	-1	-2	-4		-7	-9	-11	-10	-1	-1
6	+4	+2	0	+1	+2	+1	-1	-3	-1	+3	0	-1	0	+1	0	0	-1	-2	-3	-3	-3	-2	0	0
12&19	+7	+4	0	+1	+1	+2	+1	-7	-5	-3	-8	-11	-5	-4	-4	-3	-3	-5	-8	-11	-12	-11	-2	-3
24	+5	+3	-8	-8	-3	+1	0	-8	-5	-4	-7	-9	-4	-3	-4	-3	-3	-3	-5	-8	-9	-8	-2	-3
11&18	+3	+2	-2	-1	-3	+1	0	-7	-4	--4	-5	-7	-3	-3	-3	-3	-2	-2	-5	-9	-9	-5	-1	-2
4	+11	+6	-2	+1	+3	+2	--8	-25	-22	-7	-3	-10	-5	-3	-4	-4	-7	-13	-10	-25	-28		-8	-7
10&16	+8	+7	+8	+9	+11	+8	-4	-22	-24	-1	-9	-11	-4	-1	-2	-3	-8	-15	-20	-30	-31	-29		
21	+18	+9	+9	+6	+8	+7	+1	-5	-4	0	-7	-10	-5	-3	-2	-3	-5	-9	-11	-13	-13	-11	+1	-3
23	+12	+6	+2	+3	+6	+5	0	-5	-3	+1	-4	-7	-4	0	-1	-2	-4	-7	-9	-10	-10	-8	+1	-1
28	+1		+12	+13	+15	+11	0	-16	-13	+2	-5	-7	-1	+4	+5	+3	-1	-8	-13	-22	-23	-21	+6	+2
38			+15		+16	+13	+1	-13	-11	+5	-1	-2	+4	+8	+7	+6	+2	-5	-11	-17	-19	-18	+9	+4
40		-13	+9	+9	+12	+9	0	-11	-8	+12	-3	-4	+2	+5	+5	+4	-1	-7	-13	-19	-20	-17	+4	+3
45			+13		+16	+12	+1	-12	-10	+6	0	-1	+4	+8	+8	+7	+3	-3	-8	-14	-14	-10	+9	+5
53																								
59																								
84										-9	-2	-7	-11			-3		-3		-1				
82										-4	+2	-3	-6			-2		-2		-1				
85										-5	+3	0	+1			0		0		-1				
83										-1	+3	+1	+1			0		-2		-1				
103(1)										+2	-4	-6	0	+3	+3	+1	-3	-15	-16	-20	-9	-7		
105(1)										-4	-6	-8	-3	0	-1	-1	0	0	-1	-1	0	-1		
107(1)										+5	-1		-1	-2	-1	-1	-2	-1	-1	0	-1	-1	-1	
107(3)										+5	-2		-2	-2	-2	-1	-1	-1	-1	-1	-1	0	-1	
107(4)											-6	-7	-10	-9	-8	-7	-6	-3	--3	-3	-2	-3	-11	
107(5)										+6	-4		-4	-5	--2	0	+1	+2	+1	-2	-1	-3	-7	
109(1)										+1	-4		-3	-2	-2	-2	-2	-1	-1	-2	-1	-1	--1	
112(1)										+3	-4		-4	-4	-5	-5	-4	-4	-3	-1	-1	-3	-4	
115(1)										+5	-2		-4	-6	-4	-4	-4	-3	-3	-3	-4	-7		
118(3)										+4	-4		-6	-8	-7	-6	-6	-5	-5	-4	-5	-8		
118(4)										+4	-5		-7	-10	-7	-7	-6	-5	-5	-3	-4	-8		
118(5)										+5	-4		-5	-6	-3	-1	-1	0	-1	-1	-4	-10		
119(1)										+5	-2	-4	-4	-6	-4	-4	-4	-3	-4	-3	-5	-9		
119(3)										+5	-4	-6	-6	-8	-7	-6	-6	-5	-6	-5	-7	-13		
119(4)										+4	-6		-8	-10	-7	-6	-6	-5	-5	-5	-8	-15		
119(5)										+5	-6		-8	-10	-7	-6	-6	-5	-6	-7	-12	-20		
120(1)										+6	-1		-2	-3	-2	-2	-1	-1	-1	-1	-1	-1	-3	
120(2)										+6	-3		-3	-5	-5	-3	-3	-3	-3	-3	-3	-3	-4	
120(3)										+6	--5		-6	-8	-8	-8	-8	-7	-7	-5	-6	-12	-6	
120(4)										+6	-6		-8	-8	-8	-5	-8	-8	-7	-6	-9	-17	-8	
121(1)										+6	-1		-1	-2	-1	-1	-1	0	-1	0	-1	-2	-1	
121(2)										+6	-2		-2	-1	--1	+8	-3	-8	0	0	-1	-1	-1	
121(3)										+7	-2		-2	-2	-2	-2	-2	-1	-1	0	0	-1	-8	
121(4)										+7	-2		-2	-2	-2	-2	-2	-1	0	-1	-1	-2	-2	

*and with recommended lower bend with entire length of 24.5-foot-diameter tunnel downstream
**pressures in feet of water above or below atmospheric as indicated by the plus or minus sign
***fluctuates from -6 to -11

TABLE 4 -- CONTINUED

Tunnel pressures **

Test No.	Piezometers in the upper bend: Near pier 47	48	Along invert 49	50	51	52	53	54	55	Along crown 56	57	58	59	60	Piezometers along crown of inclined tunnel 61	62	63	64	65	66	67	Piezometers along crown of lower bend 68	68a
1&17	-6	-6	-6	+6	+15	+23	+29	+29	+15	-34	-37	-31	-23	-18	-15	-11	-11	-11	-7	-5	-5	-25	
22	+6	+5	+4	+13	+21	+27	+33	+35	+24	-13	-13	-8	-4	-3									
26	+6	+6	+4	+8	+20	+27	+32	+34	+23	-10	-10	-7	-3	-1	-3	-3	-3	-3	-3	-2	-2	-2	
5	+5	+5	+4	+7	+10	+24	+32	+31	+22	-4	-8	-5	-4	-1									
6	+1	+3	+2	+2	+3	+4	+17	+22	+12	-1	-3	-1	0	0									
12&19	+8	+7	+7	+16	+23	+30	+37	+38	+26	-9	-5	-5	-4	-4	-1	0	0	0	-1	-1	-1	-1	
24	+6	+6	+5	+9	+21	+30	+37	+37	+24	-4	-3	-3	-3	-3									
11&18	+6	+6	+4	+8	+14	+28	+35	+36	+23	-4	-3	-3	-3	-3		-2	-2	-2	-2	-2	-2	-2	
4	-4	-7	-7	+8	+18	+27	+29	+26	+8	-29	-28	-25	-26	-27									
10&16	-5	-13	-1	+11	+20	+26	+31	+23	+9	-11	-32	-31	-33	-29	-22	-14	-14	-14	-10	-11	-9	-25	
21	+8	+7	+6	-14	+22	+29	+37	+37	+26	-3	-5	-5	-4	-4									
23	+7	+6	+4	+5	+14	+29	+32	+32	+23	-2	-2	-2	-2	-2									
28	+5	+3	+7	+20	+30	+36	+41	+38	+21	-5	-17	-18	-20	-20	-9	-9	-10	-10	-9	-9	-9	-9	
38	+7	+6	+10	+24	+34	+41	+45	+43	+27	-5	-8	-7	-7	-7	-2	-2	-2	-2	-2	-3	-4	-4	
40	+9	+7	+7	+22	+33	+39	+44	+41	+25	-4	-8	-9	-8	-7	-4	-5	-5	-5	-5	-5	-5	-5	
45																							
53															-9	-9	-9	-9	-9	-9	-9	-9	
55															-7	-7	-7	-7	-6	-6		-5	-6
84																							
82																							
83																							
81																							
103(1)												-5	-4									-5	-4
105(1)												-2	-1									0	0
107(1)												-1	0									0	0
107(3)												-3	-2									-1	-1
107(4)												-2	-3									-1	-1
107(5)												-2	-3									-1	-2
108(1)												-1	-3									-1	-1
112(1)												-3	-2										
118(1)																							
118(3)																							
118(4)																							
118(5)																							
119(1)												-3	-2									-1	-1
119(3)												-7	-2									0	-1
119(4)												-9	-8										-3
119(5)												-13	-11										-6**
120(1)												-1	-2									-1	0
120(2)												-4	-4									-2	-2
120(3)												-11	-10									-7	-7
120(4)												-15	-14									-15	-16
121(1)												0	-1									0	0
121(2)												-2	-1									-1	-1
121(3)												-2	-2									-1	-1
121(4)												-3	-2									-2	-3

Test No.	Piezometers along crown of horizontal tunnel 69	70	71	72	73	Piezometers along invert of inclined tunnel 74	75	76	77	78	79	80	81	82	83	84	85	86	87	Piezometers along invert of lower bend 88	89	90	91	92
1&17	-15	-25	-5	0	0	0	0	0	0	0	+5	+5	+9	+9	+9	+22	+18	+32	+58	+126	+185	+180	+180	+162
22																								
26	-1	+1	0	0	0	+13	+9	+7	+9	+10	+10	+9	+10	+9	+9	+10	+6	+9	+23	+81	+124	+136	+140	+124
5																								
6																								
12&19	-4	-2	-1	0	0	+9	+4	+5	+5	+5	+7	+6	+8	+7	+7	+6	+4	+7	+24	+92	+133	+151	+158	+140
24																								
11&18	0	-1	-1	0	0		+4	+4	+5	+7		+5	+7	+5	+5	+6	+3	+6	+16	+83	+112	+130	+133	+115
4																								
10&16	-18	-5	0	0	0		-16	-10	-7	-13	-7	-9	-7	-9	-5	-5	-6	+5	+37	+119	+158	+176	+180	+162
21																								
23																								
28	-7	-1	-1	-1	0		0	-1	-1	-1	-1	-1	-1	-1	0	0	-4	+8	+35	+122	+162	+180	+184	+164
38	-2	-2	-2	-1	-1	+10	+7	+5	+7	+6	+5	+4	+7	+5	+6	+7	+4	+12	+42	+128	+169	+185	+191	+173
40	-4	-2	0	0	0	+9	+7	+4	+7	+6	+6	+4	+6	+4	+5	+6	+2	+11	+41	+130	+171	+189	+194	+174
45																								
53	-9	-13	-3	-2	-1		+5	+3	+4	+3	+5	+2	+3	-1	+2	+4	0	+9	+38	+126	+167	+185	+191	+173
55	-6	-5	-1	0	0		+10	+7	+9	+7	+9	+5	+7	-1	+7	+9	+10			+72	+107	+109	+120	+113
84																								
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83																								
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120(4)																								
121(1)																								
121(2)																								
121(3)																								
121(4)																								

Test No.	Piezometers along invert of horizontal tunnel 93	94	95	96	97	98	99	100	101	102	103	104	105	106	107	108	109	110	111	112	113	114
1&17	+65	+32	+14	+7	+16	+15	+15	+15	+16	+20	+13	+14	+15	+16	+14	+13	+17	+25	+20	+17	+14	+18
22																						
26	+32	+23	+14	+8	+14	+12	+12	+11	+11	+15	+13	+12	+12	+12	+11	+9	+18	+28	+18	+9	+9	+12
5																						
6																						
12&19	+41	+24	+13	+9	+12	+11	+10	+10	+12	+14	+10	+11	+12	+13	+13	+11	+14	+22	+13	+10	+11	+14
24																						
11&18	+29	+19	+11	+6	+6	+7	+7	+8	+9	+11	+8	+8	+8	+9	+9	+8	+10	+9	+7	+5	+6	+9
4																						
10&16	+59	+28	+8	+2	+9	+14	+16	+18	+18	+22	+13	+14	+15	+16	+14	+12	+17	+25	+16	+12	+12	+17
21																						
23																						
28	+61	+31	+12	+2	+12	+15	+16	+17	+18	+22	+18	+15	+15	+15	+13	+12	+19	+27	+16	+12	+13	+16
38	+66	+35	+13	+4	+13	+14	+15	+17	+17	+20	+17	+14	+15	+15	+13	+12	+18	+28	+16	+11	+12	+26
40	+65	+84	+13	+4	+13	+14	+14	+17	+17	+21	+18	+14	+14	+14	+14	+14	+18	+29	+16	+12	+13	+27
45																						
53	+65	+33	+14	+10								+15		+23				+15		+18		
55			+33	+19		+19			+17			+19		+19				+15		+18		
84																						
82																						
83																						
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103(1)																						
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**Fluctuates from -6 to -11

TABLE 5 — PRESSURES RECORDED IN THE SPILLWAY MODEL WITH THE RECOMMENDED MORNING GLORY, VENTING SYSTEM, AND TUNNEL

Pressures in the crest, in the upper bend, and in the air-intake tunnel **

Venting condition	Test No.	Discharge cfs	Gate crest el ft	Res el ft	Piezometers on invert side of morning-glory along center line of tunnel: In gate crest			In spillway face									Piezometers near pier on gate crest			Piezometers on crown side of morning-glory along center line of tunnel: In gate crest		
					10	11	13	14	15	16	17	18	19	20	21	22	23	24	26	32	33	35
All air vents open	*140.1	50,000	3548.0	3564.90	+6	-2	-4	-2	+1	+2	+2	+2	+2	+2	+2	-1	+15	+12	+10	0	-5	-8
	*140.2	35,000	3548.0	3560.87	+4	-3	-5	-4	-3	-3	-2	-2	-2	-2	-2	-2	+10	+7	+4	+1	-3	-6
	140.3	15,000	3548.0	3555.30	+4	0	-1	-2	-1	-1	-1	-1	-1	0	-1	-4	+5	+4	+2	+3	+1	-2
	141	35,000	3552.3	3564.90	+2	-4	-5	-3	-3	-3	-3	-3	-3	-3	-2	-2	+7	+5	+2	-2	-4	-6
	142	15,000	3557.8	3564.90	+3	0	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	+4	+3	+1	+2	0	-2
	143.1	35,000	3550.0	3562.70	-1	-3	-5	-3	-3	-3	-2	-3	-2	-2	-2	-2	+9	+6	+2	-1	-4	-6
	143.2	43,400	3550.0	3564.90	+2	-5	-7	-4	-4	-4	-3	-3	-3	-3	-2	-3	+11	+7	+4	-2	-6	-8
	143.3	15,000	3550.0	3557.30	+3	0	-1	-2	-2	-2	-2	-2	-2	-2	-2	-2	+5	+3	+1	+2	0	-2
	*144	15,000	3552.0	3559.30	+3	0	-1	-2	-1	-2	-1	-2	-2	-2	-2	-2	+5	+3	+1	+2	0	-2
	145.1	15,000	3556.0	3563.30	+3	0	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	+5	+3	+2	+2	0	-2
	145.2	20,800	3556.0	3564.90	+3	-1	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	+5	+3	+2	+1	-1	-4
	146	8,300	3560.0	3564.90	+3	+1	0	-1	-1	-1	-1	-1	-1	-1	-1	-1	+3	+3	+2	+3	+1	0
Vents under gate crest closed; vent in upper bend open	147	8,320	3560.0	3564.90	+3	+1	0	-1	-1	-1	-1	-1	-1	-1	-1	-1	+3	+3	+1	+3	+1	0
	148.1	21,150	3556.0	3564.90	+3	-1	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	+5	+4	+2	+1	-1	-3
	148.2	15,000	3556.0	3563.28	+3	0	-1	-1	-1	-1	-1	-2	-1	-1	-1	-1	+5	+3	+1	+2	0	-2
	149.1	37,500	3552.0	3564.90	+1	-6	-10	-9	+4	+3		-2	-3	-3	-4	-7	+7	+4	0	-4	-8	-12
	149.2	15,000	3552.0	3559.14	+3	0	-2	-2	+6	+1		-1	-1	-1	-1	-4	+4	+3	+1	+2	0	-3
	150.1	45,260	3550.0	3564.90	-1	-4	-12	-11	+1	-2		-5	-4	-3	-4	-5	+10	+7	+3	-5	-10	-15
	150.2	35,000	3550.0	3562.49	+2	-5	-9	-8	+1	-1		-3	-3	-2	-3	-7	+7	+5	+1	-2	-6	-11
	150.3	15,000	3550.0	3557.23	+3	0	-1	-3	-3	-3		-2	-2	-2	-2	-2	+5	+3	+2	+2	0	-2
	151.1	50,000	3548.0	3564.90	+5	-5	-7	-4	0	+2		+2	+2	+3	+2	-1	+14	+12	+9	-1	-6	-9
All air vents closed	152	8,540	3560.0	3564.90	+3	+1	0	-1	-1	-1	-1	-1	-1	-1	-1	-1	+3	+3	+2	+3	+1	0
	153.1	21,200	3556.0	3564.90	+2	-1	-3	-2	-2	-2	-2	-2	-2	-2	-2	-2	+5	+4	+2	+1	-1	-3
	153.2	15,000	3556.0	3563.24	+3	0	-1	-2	-2	-2	-3	-2	-2	-1	-1	-1	+4	+3	+2	+2	0	-2
	154.1	37,330	3552.0	3564.90	0	-7	-10	-9	+4	+3		-3	-3	-3	-4	-7	+7	+4	+1	-4	-8	-12
	154.2	15,000	3552.0	3559.14	+3	0	-2	-2	-6	+1		-1	-1	-1	-1	-4	+5	+3	+1	+2	-1	-3
	155.1	45,340	3550.0	3564.90	0	-9	-12	-11	+1	-2		-5	-4	-3	-4	-7	+10	+6	+2	-5	-10	-15
	155.2	35,000	3550.0	3562.49	+2	-5	-8	-8	+2	-1		-3	-3	-3	-3	-7	+8	+5	+1	-2	-6	-11
	155.3	15,000	3550.0	3557.20	+4	0	-1	-3	-3	-3		-2	-2	-1	-2	-2	+5	+3	+1	+2	0	-2
	156.1	52,000	3548.0	3564.90	+4	-6	-10	-9	-6	-5		-4	-3	-3	-4	-7	+14	+11	+8	-3	-9	-13

Test No.	Piezometers on crown side of morning-glory along center line of tunnel: In spillway face									Piezometers in the upper bend: Along invert			Along crown			Near vent		Piezometers in the crest structure under the gate lip								Piezometers in the air-intake tunnel		
	36	37	38	39	40	41	42	43	44	49	52	55	57	58	60	210	213	201	202	203	204	205	206	207	208	209	211	212
*140.1	-3	-3	-3	-2	-2	+1	+1	-3	-8	+11	+41	+33	-8	-6	-6	-4	-3	+9	0	-4	-4	-4	-3	-1	+1	0	-1	-1
*140.2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-3	+37	+20	-2	-1	-2	-2	-2	+2	-3	-3	-3	-3	-3	-3	-3	-3	-2	-3
140.3	-2	-1	-1	-1	-2	-1	-1	-2	-3	+1	+11	+14	-1	-1	-1	-1	-1	+1	-1	-1	-2	-2	-1	-1	-1	0	-1	-1
141	-3	-3	-3	-3	-3	-3	-3	-3	-3	-4	+39	+20	-2	-1	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-2	-2	-2
142	-1	-1	-1	-2	-1	-1	-1	-1	-1	-1	+14	+17	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
143.1	-3	-3	-3	-3	-3	-3	-3	-3	-3	-4	+38	+20	-2	-2	-2	0	-3	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-3
143.2	-4	-4	-4	-4	-4	-3	-3	-3	-3	+5	+40	+24	-4	-4	-5	-2	-4	-2	-4	-4	-4	-4	-4	-4	-4	-2	-2	-3
143.3	-1	-1	-1	-1	-1	-1	-1	-2	-2	-1	+12	+20	-2	-2	-2	-2	-2	-1	-1	-1	-2	-1	-1	-1	-1	-2	-2	-2
*144	-1	-1	-1	-2	-2	-2	-2	-2	-2	-1	+11	+19	-2	-2	-2	-2	-2	-1	-2	-2	-2	-2	-1	-1	-1	-1	-2	-2
145.1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	+18	+19	-1	-1	-2	-2	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
145.2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	+42	+13	-1	-1	-1	-2	-2	-2	-2	-2	-2	-2	-2	-1	-2	-2	-2	-2
146	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	+8	+16	-2	0	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	0	-1	-1
147	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	+5	+16	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
148.1	-2	-2	-2	-2	-2	-2	-2	-2	-2	-1	+42	+13	-1	-2	0	-2	-2	-2	-2	-2	-2	-2	-3	-2	-2	-2	-2	-2
148.2	-1	-1	-1	-1	-2	-1	-1	-2	-1	-1	+18	+18	-1	-1	-1	-1	-1	-1	-2	-1	-1	-1	-2	-1	-1	-1	-2	-2
149.1	-9	+3	+3	-1	-3	-4	-4	-7	-11	+2	+35	+25	-4	-3	-4	-6	-4	-5	-8	-9	-9	-9	-8	-7	-7	-2	-1	-1
149.2	-2	+5	+1	-1	-2	-2	-1	-2	-5	+1	+18	+16	-2	-1	-1	-2	-2	-1	-2	-2	-2	-2	-2	-2	-2	0	0	0
150.1	-12	-1	-4	-5	-5	-5	-5	-8	-12	+8	+37	+25	-5	-6	+2	-5	-3	-5	-11	-12	-14	-14	-12	-9	-8	-5	-3	-4
150.2	-8	+5	-2	-4	-4	-4	-4	-6	-10	+2	+34	+24	-4	-4	+3	-5	-3	-6	-8	-8	-10	-10	-9	-8	-7	0	-3	-4
150.3	-3	-3	-3	-3	-3	-3	-3	-2	-2	-1	+8	+19	-2	-2	-2	-3	-2	-1	-1	-3	-3	-1	-1	-1	-1	-2	-3	-3
151.1	-7	-2	-1	-1	-1	-1	-2	-5	-11	+12	+41	+25	-7	-7	-7	-6	-4	+8	0	-6	-9	-9	-5	-2	+1	-5	-1	-2
152	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	+5	+16	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
153.1	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	+35	+16	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2
153.2	-1	-1	-1	-1	-2	-2	-1	-2	-1	-1	+15	+21	-2	-1	-1	-2	-1	-1	-2	-1	-1	-1	-4	-1	-1	-1	-2	-1
154.1	-9	+3	+2	-1	-3	-4	-5	-7	-12	+2	+35	+15	-3	-3	-3	-6	-4	-5	-8	-9	-10	-9	-8	-8	-7	-3	-3	-3
154.2	-2	+5	+1	-1	-1	-1	-1	-2	-5	+1	+11	+15	-1	-1	-1	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	0	0	0
155.1	-12	-1	-4	-5	-6	-6	-6	-9	-14	+7	+36	+25	-16	-8	+2	-6	-5	-5	-11	-12	-14	-14	-12	-10	-9	-11	-7	-7
155.2	-8	+1	-2	-4	-4	-4	-4	-6	-11	+2	+33	+23	-3	-4	+3	-6	-3	-6	[illegible]	-9	-10	-10	-9	-8	-7	-3	-4	-5
155.3	-3	-3	-3	-3	-3	-3	-3	-2	-3	-1	+10	+19	-2	-2	-2	-3	-2	-2	-2	-3	-3	-1	-1	-1	-1	-3	-3	-3
156.1	-12	-7	-7	-6	-6	-7	-7	-11	-18	+7	+35	+22	-24	-16	-10	-12	-13	+5	-5	-11	-14	-15	-9	-6	-3	-15	-14	-12

TABLE 5 — CONTINUED

Pressures in spillway tunnel **

Venting condition	Test No.	Discharge cfs	Gate crest el ft	Res el ft	Piezometers along crown of: Inclined tunnel					Lower bend		Horizontal tunnel				Piezometers along invert of: Inclined tunnel					Lower bend			Horizontal tunnel		
					62	63	64	65	66	68	68a	70	71	72	73	76	78	80	82	84	88	90	92	100	107	113
All vents open	*140.1	50,000	3548.0	3564.9	-4	-3	-4	-3	-3	-2	-2	-1	-1	0	0	+8	+9	+8	+5	+8	+70	+114	+95	+13	+10	+13
	*140.2	35,000	3548.0	3560.87	0	0	-1	0	0	0	0	0	0	0	0	+7	+7	+7	+4	+6	+54	+89	+74	+7	+7	+10
	140.3	15,000	3548.0	3555.3	-1	-1	-1	-1	0	0	0	0	0	0	0	+3	+4	+5	+2	+3	+30	+53	+36	+5	+5	+6
	141	35,000	3552.31	3564.9	-1	-1	-1	-2	-1	0	0	-1	0	0	0	+6	+6	+7	+4	+6	+53	+90	+71	+11	+7	+10
Vents under gate crest closed; vent in upper bend open	151.1	50,000	3548.0	3564.9	-6	-6	-6	-5	-3	-3	-4	-1	0	0	0	+8	+9	+8	+4	+8	+71	+116	+96	+14	+11	+14
	151.2	35,000	3548.0	3560.76	-1	-1	-1	-1	-1	-1	-1	0	0	0	0	+6	+9	+11	+4	+6	+56	+87	+75	+11	+8	+10
	151.3	15,000	3548.0	3555.25	0	-1	-1	0	0	0	0	0	0	0	0	+3	+4	+5	+1	+3	+32	+48	+38	+6	+5	+6
All vents closed	156.1	52,000	3548.0	3564.9	-8	-8	-8	-6	-3	-3	-2	-2	-1	0	0	+7	+8	+9	+6	+9	+72	+119	+97	+15	+11	+14
	156.2	35,000	3548.0	3560.8	-1	-1	+1	0	0	0	+1	0	0	0	0	+7	+8	+11	+4	+7	+59	+91	+76	+11	+9	+11
	156.3	15,000	3548.0	3555.29	0	0	-1	0	0	0	0	0	0	0	0	+3	+5	+5	+2	+3	+31	+48	+37	+6	+6	+6

*Scheduled operating conditions
**Pressures are in feet of water above or below atmospheric as indicated by plus or minus sign

FIGURE 14

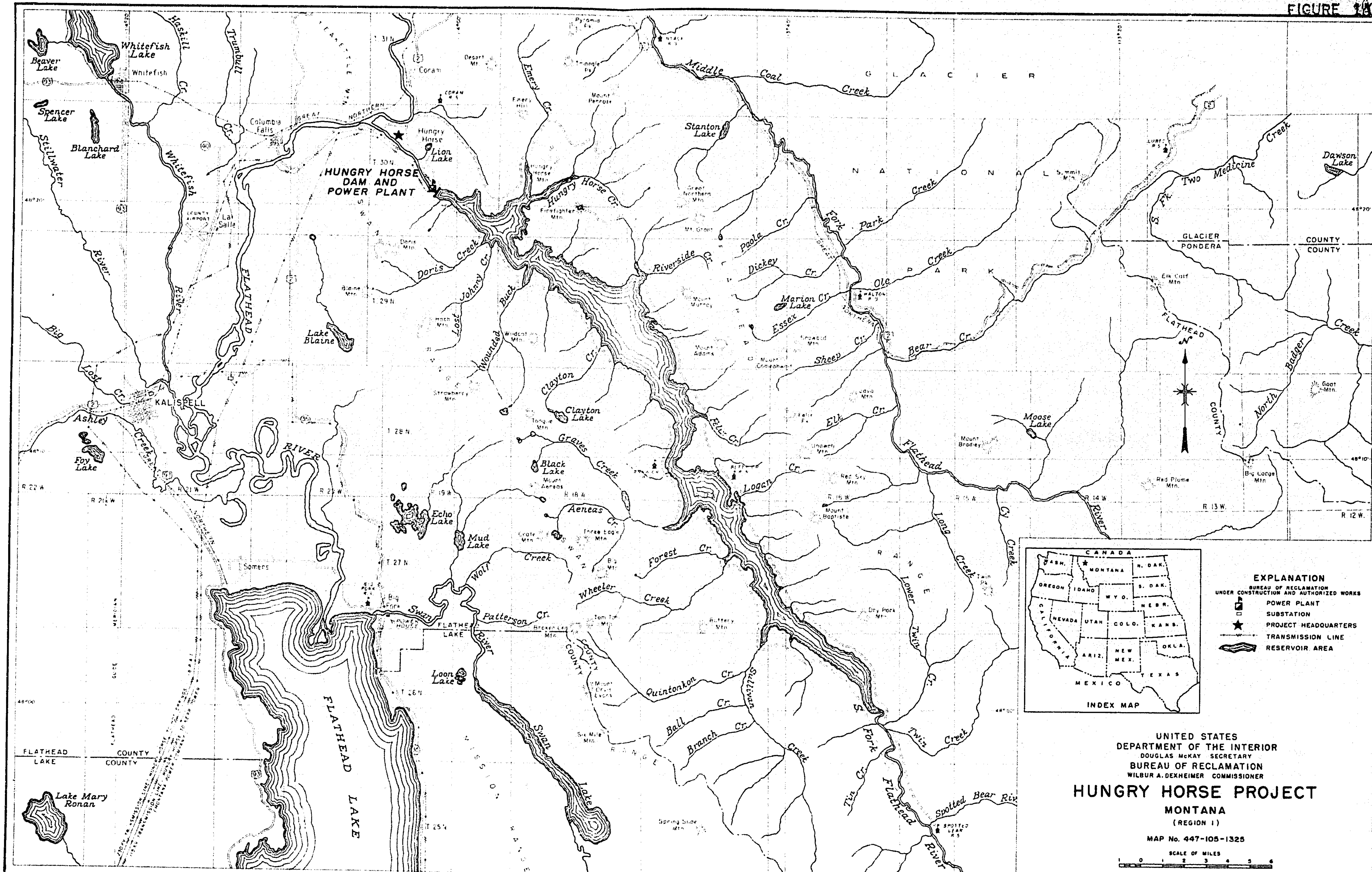
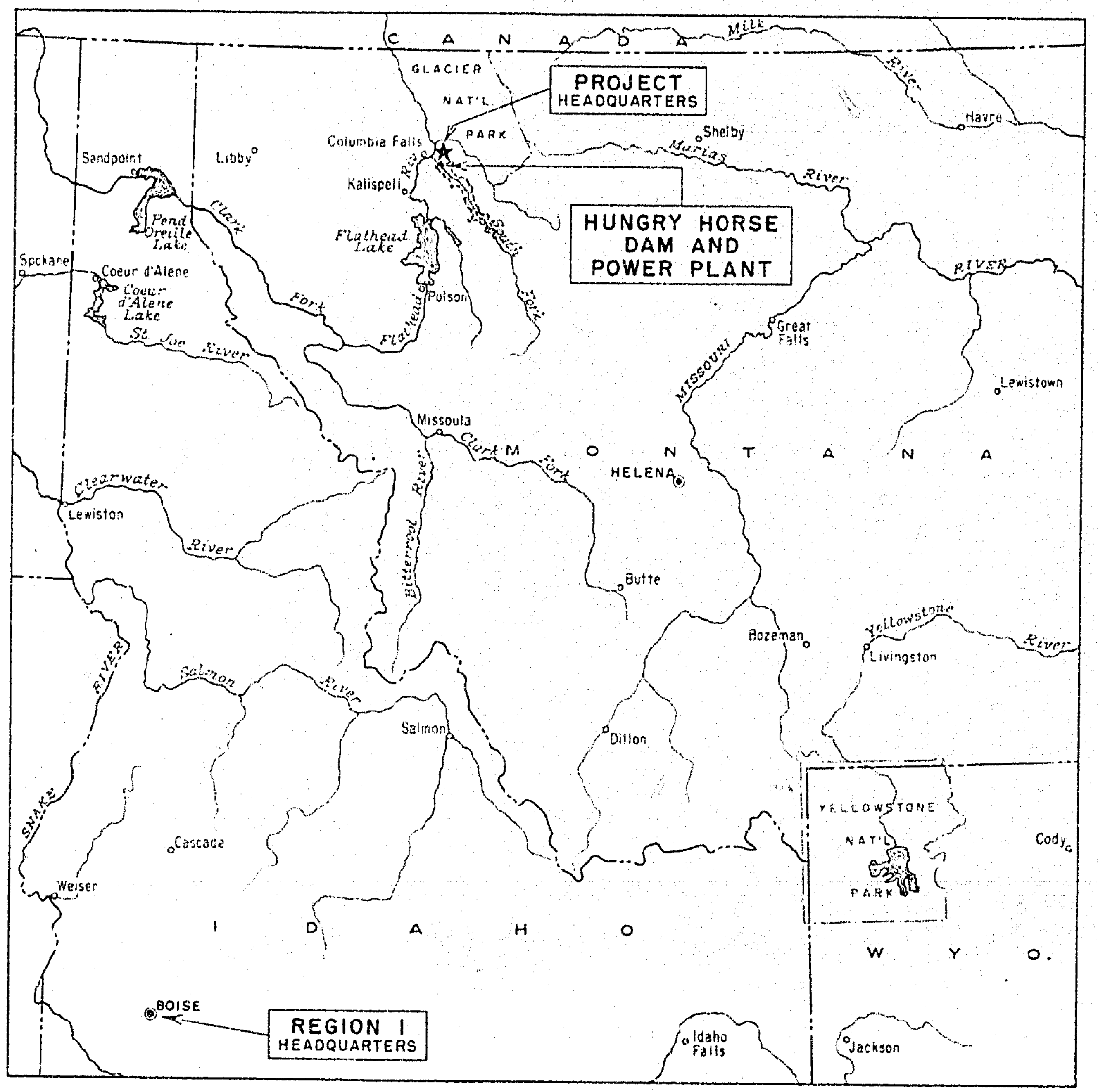

HUNGRY HORSE DAM AND POWER PLANT
Whitefish Lake
Whitefish
Beaver Lake
Spencer Lake
Blanchard Lake
Stillwater River
Whitefish River
Haskill Cr.
Trumbull Cr.
Columbia Falls
Coram
Hungry Horse
Lion Lake
Hungry Horse Cr.
Emery Cr.
Middle Fork
Coal Creek
Stanton Lake
GLACIER NATIONAL PARK
Park Creek
Paola Cr.
Riverside Cr.
Dickey Cr.
Marion Cr.
Marion Lake
Essex Cr.
Ole Creek
Bear Cr.
Sheep Cr.
Two Medicine Creek
Dawson Lake
S. Fk.
GLACIER COUNTY
PONDERA COUNTY
FLATHEAD COUNTY
North Badger Creek
Moose Lake
Flathead River
Cy Creek
Long Creek
Lower Twin Cr.
Twin Creek
Spotted Bear River
S. Fork Flathead River
Tin Cr.
Sullivan Creek
Branch Cr.
Ball Cr.
Quintonkon Cr.
Wheeler Creek
Forest Cr.
Logan Cr.
Elk Cr.
Graves Creek
Aeneas Cr.
Clayton Cr.
Clayton Lake
Black Lake
Wounded Buck Cr.
Lost Johnny Cr.
Doris Creek
Lake Blaine
FLATHEAD RIVER
KALISPELL
Big Cr.
Lost Cr.
Ashley Creek
Foy Lake
Echo Lake
Mud Lake
Wolf Creek
Swan River
Patterson Cr.
FLATHEAD LAKE
Somers
Bigfork
Loon Lake
Swan Lake
Lake Mary Ronan
FLATHEAD LAKE COUNTY
LAKE COUNTY
SWAN RANGE
MISSION RANGE
R 22 W
R 21 W
R 20 W
R 19 W
R 18 W
R 15 W
R 14 W
R 13 W
R 12 W
T 31 N
T 30 N
T 29 N
T 28 N
T 27 N
T 26 N
T 25 N
N
INDEX MAP
CANADA
WASH.
MONTANA
N. DAK.
OREGON
IDAHO
S. DAK.
WYO.
NEBR.
CALIFORNIA
NEVADA
UTAH
COLO.
KANS.
ARIZ.
NEW MEX.
OKLA.
TEXAS
MEXICO
EXPLANATION
BUREAU OF RECLAMATION
UNDER CONSTRUCTION AND AUTHORIZED WORKS
POWER PLANT
SUBSTATION
PROJECT HEADQUARTERS
TRANSMISSION LINE
RESERVOIR AREA
UNITED STATES
DEPARTMENT OF THE INTERIOR
DOUGLAS McKAY SECRETARY
BUREAU OF RECLAMATION
WILBUR A. DEXHEIMER COMMISSIONER
HUNGRY HORSE PROJECT
MONTANA
(REGION 1)
MAP No. 447-105-1325
SCALE OF MILES
0 1 2 3 4 5 6
JULY 1953

FIGURE 1B



FACTUAL DATA - HUNGRY HORSE PROJECT

DESCRIPTION OF PROJECT

HUNGRY HORSE DAM is a key project in the long-range program for multiple-purpose development of the water resources of the vast Columbia River drainage. Situated as it is, near the headwaters of one of the principal Columbia River tributaries, it provides water for power generation at a number of downstream plants on the Flathead, Clark Fork, Pend Oreille and Columbia Rivers. It contributes materially toward controlling floods on the Columbia River and its tributaries; helps eliminate floods in the Flathead Valley; and reduces peak discharges between there and Grand Coulee Dam from 25 to 10 percent, and at Portland, Oregon, by about 5 percent, or 9 inches on a 15-foot flood crest. Prospects for irrigation development in the Flathead Valley are enhanced by the dam.

Original surveys were initiated in 1921 by the Geological Survey of the Department of the Interior. They were continued by the Bureau of Reclamation and other Federal agencies as a basis for Congressional approval of the project. On June 5, 1944, Congress authorized the Secretary of the Interior to undertake construction of Hungry Horse Dam.

WATER SUPPLY AND CLIMATE

The South Fork of the Flathead River Basin above the U. S. Geological Survey gage, three miles downstream from Hungry Horse Dam and two miles above the confluence with the Flathead River, has a drainage area of 1,640 square miles and an average discharge of 3,118 cubic feet per second (1928-32, 1933-48). The maximum annual runoff is approximately 3,500,000 acre-feet and the minimum is 1,400,000 acre-feet. Daily maximum discharge observed, 46,200 c.f.s. on June 19, 1916; minimum, 206 c.f.s. on December 6, 1935. Annual precipitation, 27 to 30 inches. Temperature, maximum 95°, minimum 40° below zero, mean 40.6° (data for years 1948, 1949 and 1950) at Hungry Horse Government Camp.

FEATURES OF THE PROJECT PLAN

HUNGRY HORSE RESERVOIR back of the dam, located entirely in the Flathead National Forest, has a capacity of 3,468,000 acre-feet at maximum water surface elevation of 3,560 feet above sea level, and dead storage of 45,000 acre-feet at elevation 3,200 feet, the centerline of the outlet pipes.

Over 3,000,000 acre-feet of the reservoir capacity may be used for power production through the penstocks. The reservoir has a surface area of 22,500 acres and a shore line of 115 miles. The maximum depth is 460 feet at the dam.

HUNGRY HORSE DAM is located 5.2 miles above the confluence of the South Fork of the Flathead with the main Flathead River. It is a concrete arch-gravity dam having a structural height of 564 feet. The crest length is 2,115 feet, width 39 feet, with a base width of 300 feet. The crest of the dam is at elevation 3,565 feet above sea level. A total of 2,950,000 cubic yards of concrete was placed in the dam. The normal high water surface is at elevation 3,560 and the minimum tail water surface is at elevation 3074.5, a difference of 485.5 feet.

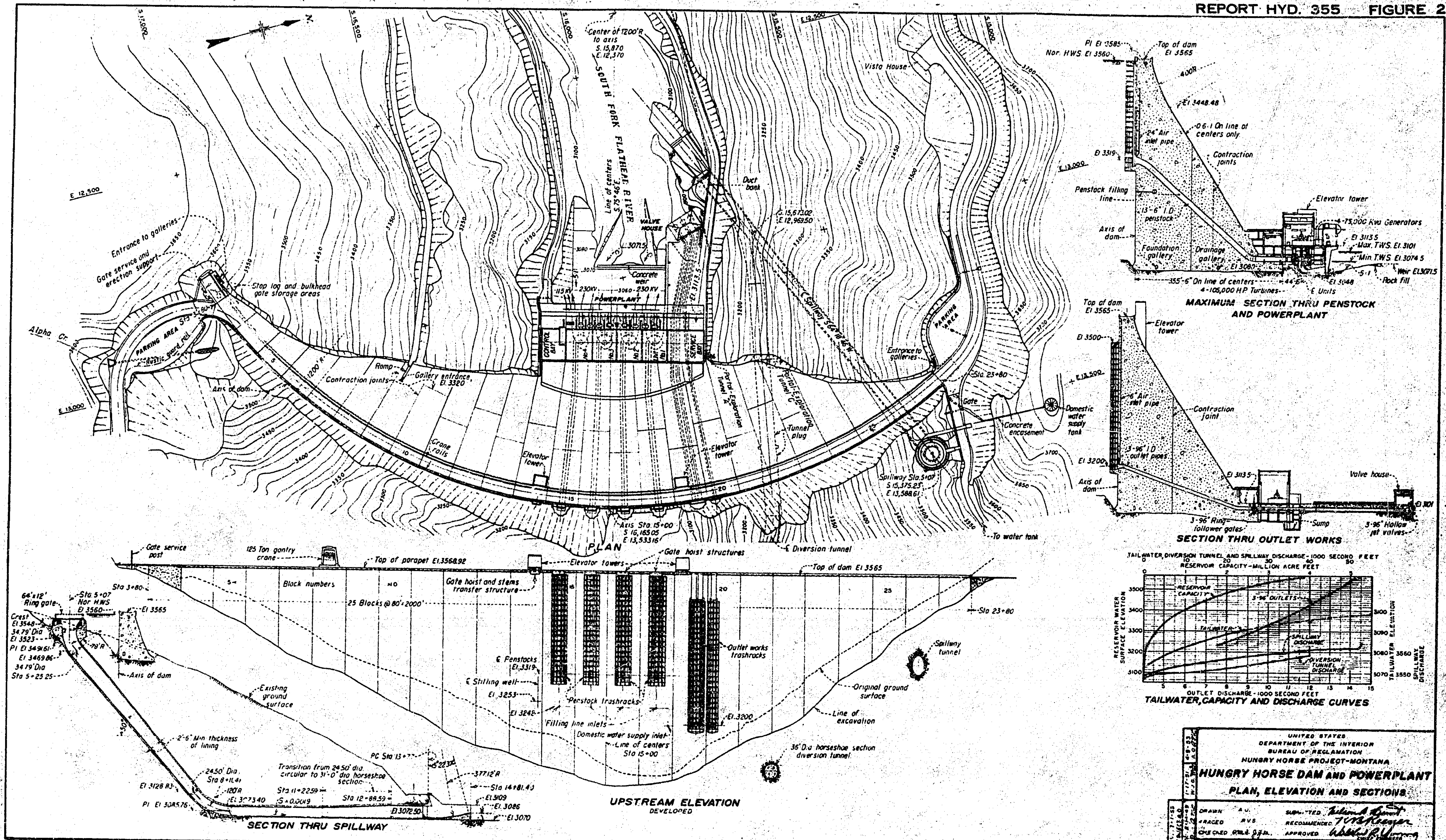
A ring gate (morning-glory type) spillway leading to an inclined tunnel varying in diameter from 24.5 feet to 35 feet, having an over-all length of 1,125 feet, has a maximum capacity of 45,000 cubic feet per second. A 65-foot-diameter ring gate, having a rise of 12 feet, controls passage of water through the spillway.

Additional regulation of the river flow excess, over that through the penstocks, is provided by the two 96-inch-diameter steel outlet pipes through the dam. The elevation at the intake end is 3,200 feet. Water flow in each pipe is controlled by a 96-inch ring follower gate and a hollow-jet valve. Capacity of each is 4,750 cubic feet per second.

A POWER PLANT, located in a building 394 feet long at the toe of the dam, has a generating capacity of 285,000 kw. of power through four, Francis type, vertical shaft turbines. Each turbine is 105,000 horsepower, direct connected to a 71,250 kw. generator. The turbines will be operated under hydraulic heads from 250 feet to 485.5 feet. Four steel penstocks each approximately 490 feet long and 13 feet 6 inches maximum diameter, take the water through the dam to the turbines, with the flow controlled by wicket gates in the turbine and by fixed wheel gates at the upstream end of the penstocks.

THE SWITCHYARD is located on the right bank immediately below the dam and power plant. The Bonneville Power Administration takes delivery of all energy produced at Hungry Horse Project Power Plant and transmits it to load centers over its 115- and 230-kilovolt lines.

GPO 985512


PLAN
SOUTH FORK FLATHEAD RIVER
POWERPLANT
VALVE HOUSE
CONTROL BAY
SERVICE BAY
Vista House
Entrance to galleries
Gate service and erection support
Stop log and bulkhead gate storage areas
PARKING AREA
Alpha Cr.
Axis of dam
Contraction joints
Gallery entrance El. 3320
Ramp
Crane rails
Elevator tower
Portal-Exploration Tunnel "A"
Portal-Exploration Tunnel "C"
Tunnel plug
Duct bank
Spillway Sta. 5+07
Domestic water supply tank
Concrete encasement
To water tank
Diversion tunnel
Axis Sta. 15+00
UPSTREAM ELEVATION
DEVELOPED
Top of parapet El. 3568.92
Top of dam El. 3565
125 Ton gantry crane
Gate hoist structures
Elevator towers
Block numbers
25 Blocks @ 80' = 2000'
Gate hoist and stems transfer structure
Penstocks El. 3319
Stilling well
Penstock trashracks
Filling line inlets
Domestic water supply inlet
Line of centers Sta 15+00
Outlet works trashracks
Spillway tunnel
Original ground surface
Line of excavation
35' Dia horseshoe section diversion tunnel
SECTION THRU SPILLWAY
64'x12' Ring gate
Crest El. 3548
Existing ground surface
2'-6" Min thickness of lining
Transition from 24.50' dia circular to 31'-0" dia horseshoe section
MAXIMUM SECTION THRU PENSTOCK AND POWERPLANT
Top of dam El. 3565
Nor. HWS El. 3560
24" Air inlet pipe
Contraction joints
Penstock filling line
13'-6" I.D. penstock
Foundation gallery
Drainage gallery
Elevator tower
4-75,000 Kva Generators
Max. TWS. El. 3101
Min. TWS. El. 3074.5
Rock fill
4-105,000 H.P. Turbines
SECTION THRU OUTLET WORKS
Elevator tower
Contraction joint
3'-96" I.D. outlet pipes
Valve house
Sump
3'-96" Ring-follower gates
3'-96" Hollow jet valves
TAILWATER, CAPACITY AND DISCHARGE CURVES
TAILWATER DIVERSION TUNNEL AND SPILLWAY DISCHARGE - 1000 SECOND FEET
RESERVOIR CAPACITY - MILLION ACRE FEET
OUTLET DISCHARGE - 1000 SECOND FEET
RESERVOIR WATER SURFACE ELEVATION
TAILWATER ELEVATION
SPILLWAY DISCHARGE
RESERVOIR CAPACITY
3-96" OUTLETS
TAILWATER
DIVERSION TUNNEL DISCHARGE
UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
HUNGRY HORSE PROJECT-MONTANA
HUNGRY HORSE DAM AND POWERPLANT
PLAN, ELEVATION AND SECTIONS
DENVER, COLORADO, DEC. 31, 1947
447-D-183
RECORD DRAWINGS

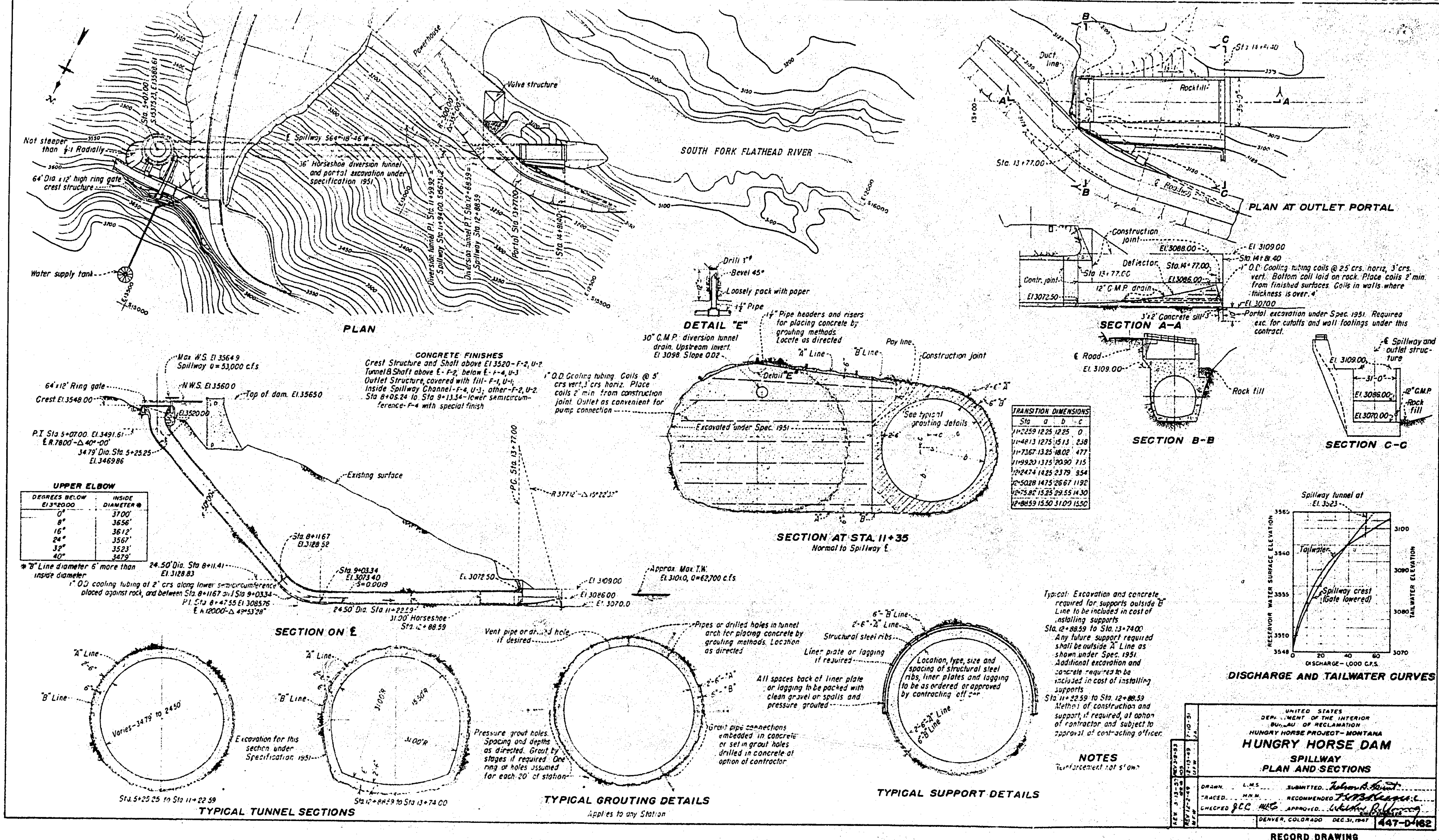

PLAN
SOUTH FORK FLATHEAD RIVER
Powerhouse
Valve structure
Not steeper than ½:1 Radially
64' Dia. x 12' high ring gate crest structure
Water supply tank
℄ Spillway S64°-18'-46"W
36' Horseshoe diversion tunnel and portal excavation under specification 1951
DETAIL "E"
Drill 1"ø
Bevel 45°
Loosely pack with paper
1½" Pipe
PLAN AT OUTLET PORTAL
Duct line
Rockfill
Sta. 13+77.00
Sta. 14+81.40
SECTION A-A
Construction joint
Deflector
Contr. joint
12" C.M.P. drain
El. 3109.00
El. 3088.00
El. 3086.00
El. 3072.50
El. 3070.0
1" O.D. Cooling tubing coils @ 2.5' crs. horiz., 3' crs. vert. Bottom coil laid on rock. Place coils 2' min. from finished surfaces. Coils in walls where thickness is over 4'.
3'x2' Concrete sill
Portal excavation under Spec. 1951. Required exc. for cutoffs and wall footings under this contract.
SECTION B-B
℄ Road
Rock fill
SECTION C-C
℄ Spillway and outlet structure
CONCRETE FINISHES
Crest Structure and Shaft above El. 3520 - F-2, U-2
Tunnel & Shaft above ℄ - F-2, below ℄ - F-4, U-3
Outlet Structure, covered with fill - F-1, U-1;
Inside Spillway Channel - F-4, U-3; other - F-2, U-2.
Sta. 8+05.24 to Sta. 9+13.34 - lower semicircumference - F-4 with special finish
Max. W.S. El. 3564.9
Spillway Q = 53,000 c.f.s.
64' x 12' Ring gate
Crest El. 3548.00
N.W.S. El. 3560.0
Top of dam El. 3565.0
Existing surface
UPPER ELBOW
SECTION ON ℄
Approx. Max. T.W. El. 3101.0, Q = 62,700 c.f.s.
30" C.M.P. diversion tunnel drain. Upstream invert El. 3098. Slope 0.02
1½" Pipe headers and risers for placing concrete by grouting methods. Locate as directed
"A" Line
"B" Line
Pay line
Construction joint
Excavated under Spec. 1951
See typical grouting details
SECTION AT STA. 11+35
Normal to Spillway ℄
TRANSITION DIMENSIONS
Spillway tunnel at El. 3523
Tailwater
Spillway crest (Gate lowered)
RESERVOIR WATER SURFACE ELEVATION
TAILWATER ELEVATION
DISCHARGE - 1,000 C.F.S.
DISCHARGE AND TAILWATER CURVES
Excavation for this section under Specification 1951
Sta. 5+25.25 to Sta. 11+22.59
Sta. 12+88.59 to Sta. 13+74.00
TYPICAL TUNNEL SECTIONS
Vent pipe or drilled hole if desired
Pipes or drilled holes in tunnel arch for placing concrete by grouting methods. Location as directed
Pressure grout holes. Spacing and depths as directed. Grout by stages if required. One ring of holes assumed for each 20' of station
Grout pipe connections embedded in concrete or set in grout holes drilled in concrete at option of contractor
TYPICAL GROUTING DETAILS
Applies to any Station
Structural steel ribs
Liner plate or lagging if required
All spaces back of liner plate or lagging to be packed with clean gravel or spalls and pressure grouted
Location, type, size and spacing of structural steel ribs, liner plates and lagging to be as ordered or approved by contracting officer
TYPICAL SUPPORT DETAILS
NOTES
Reinforcement not shown
UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
HUNGRY HORSE PROJECT - MONTANA
HUNGRY HORSE DAM
SPILLWAY
PLAN AND SECTIONS
DENVER, COLORADO DEC. 31, 1947
447-D-162
RECORD DRAWING

FIGURE 4
REPORT HYD. 355

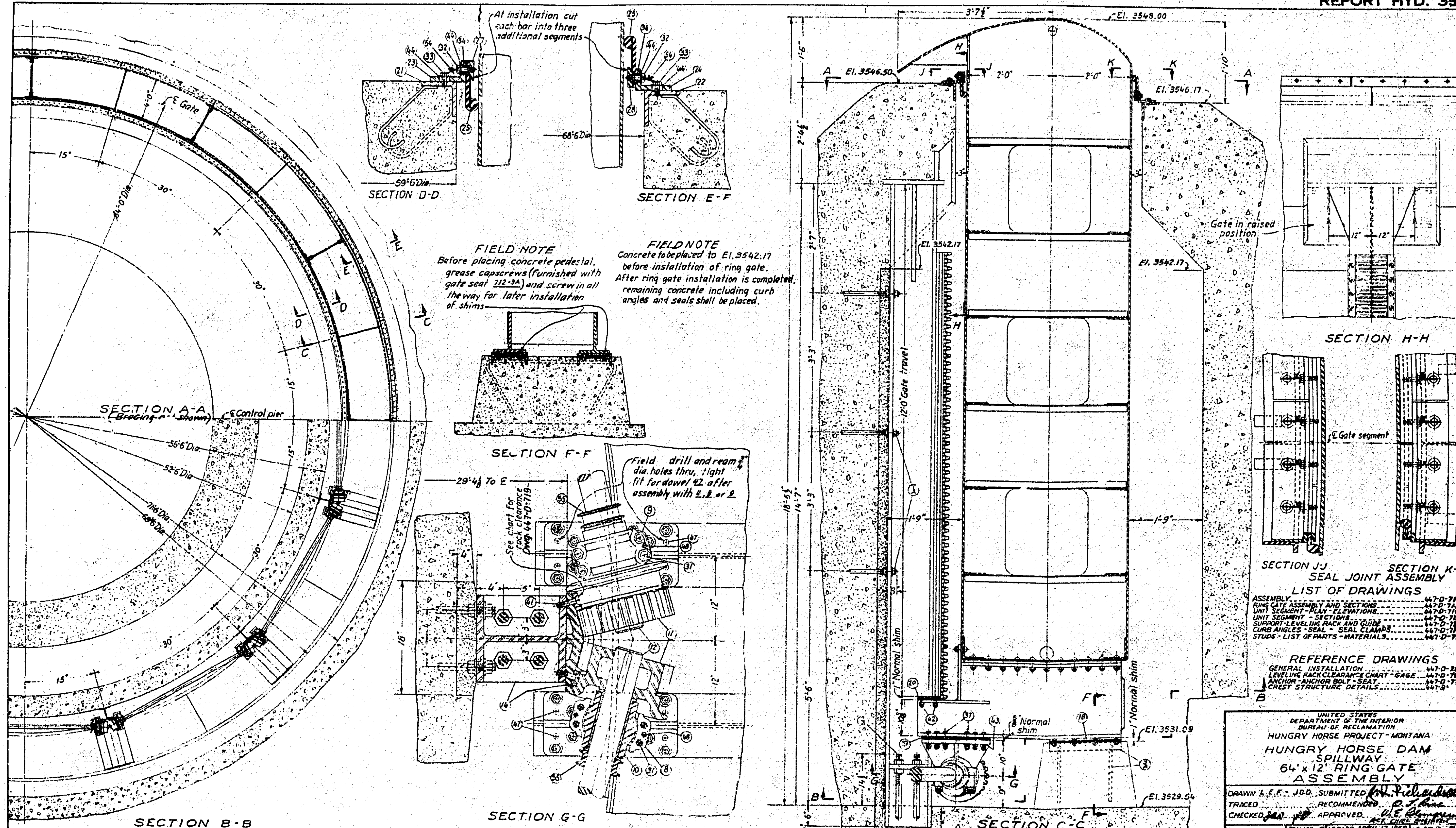
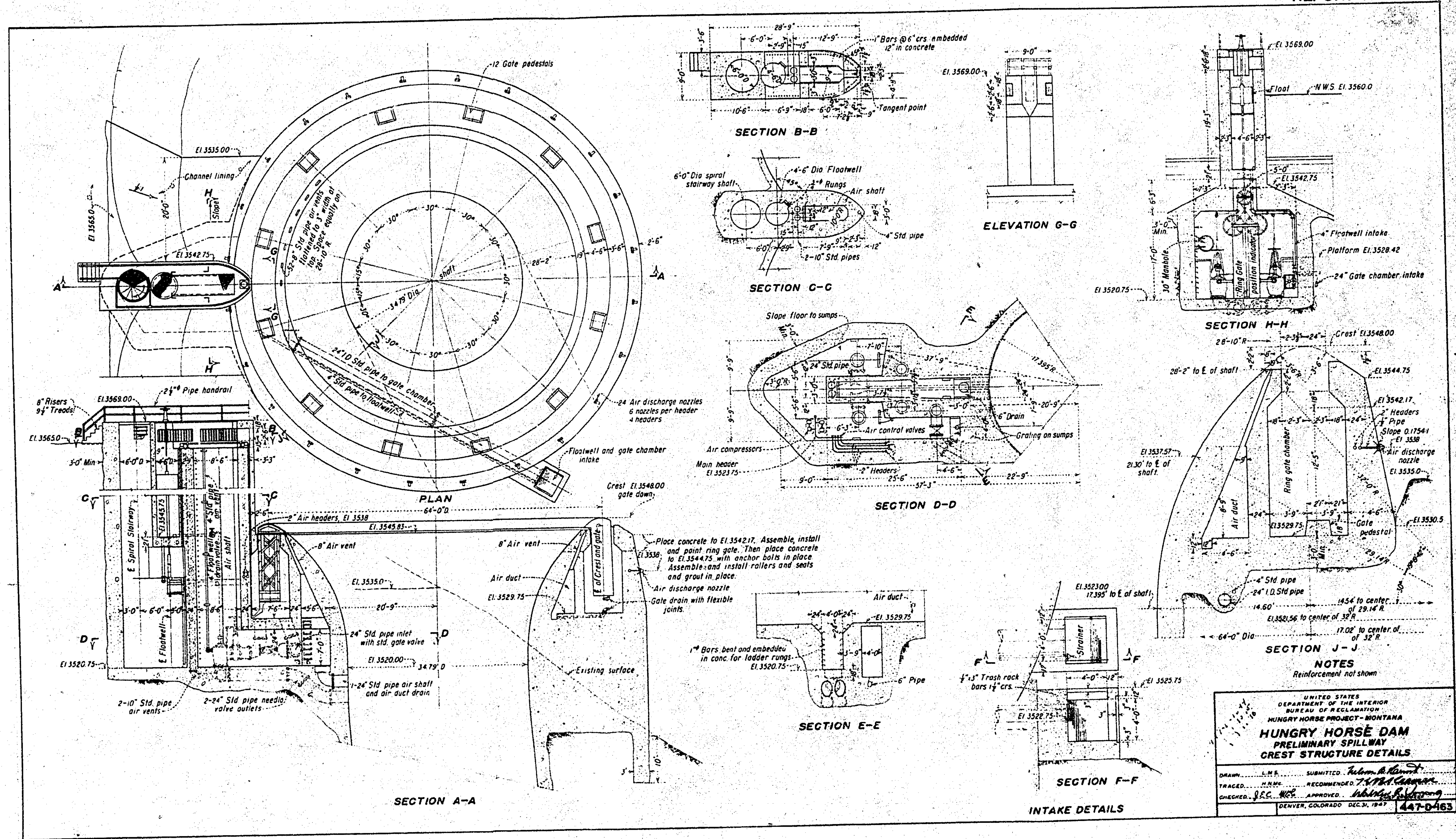


FIGURE 5
REPORT HYD. 355



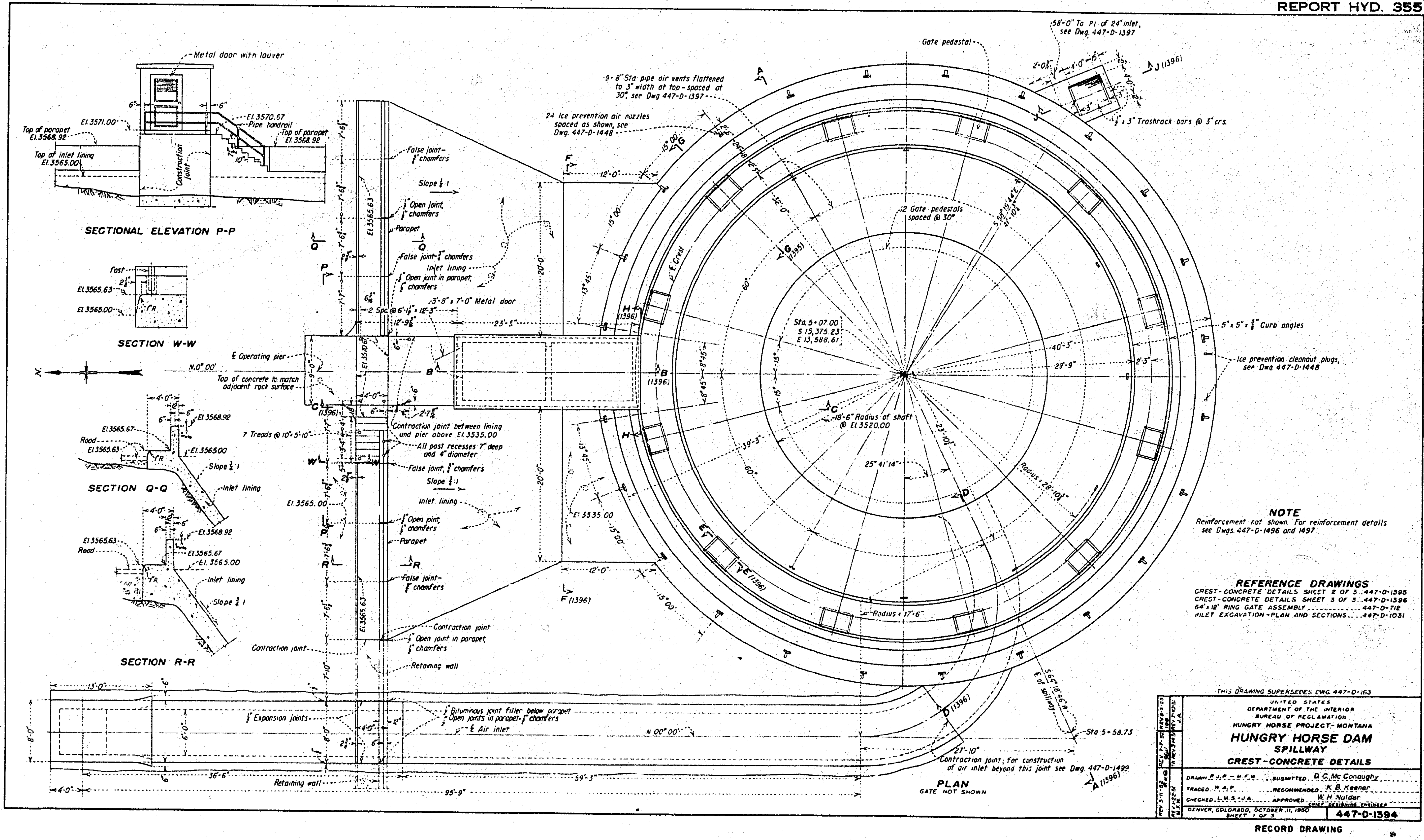
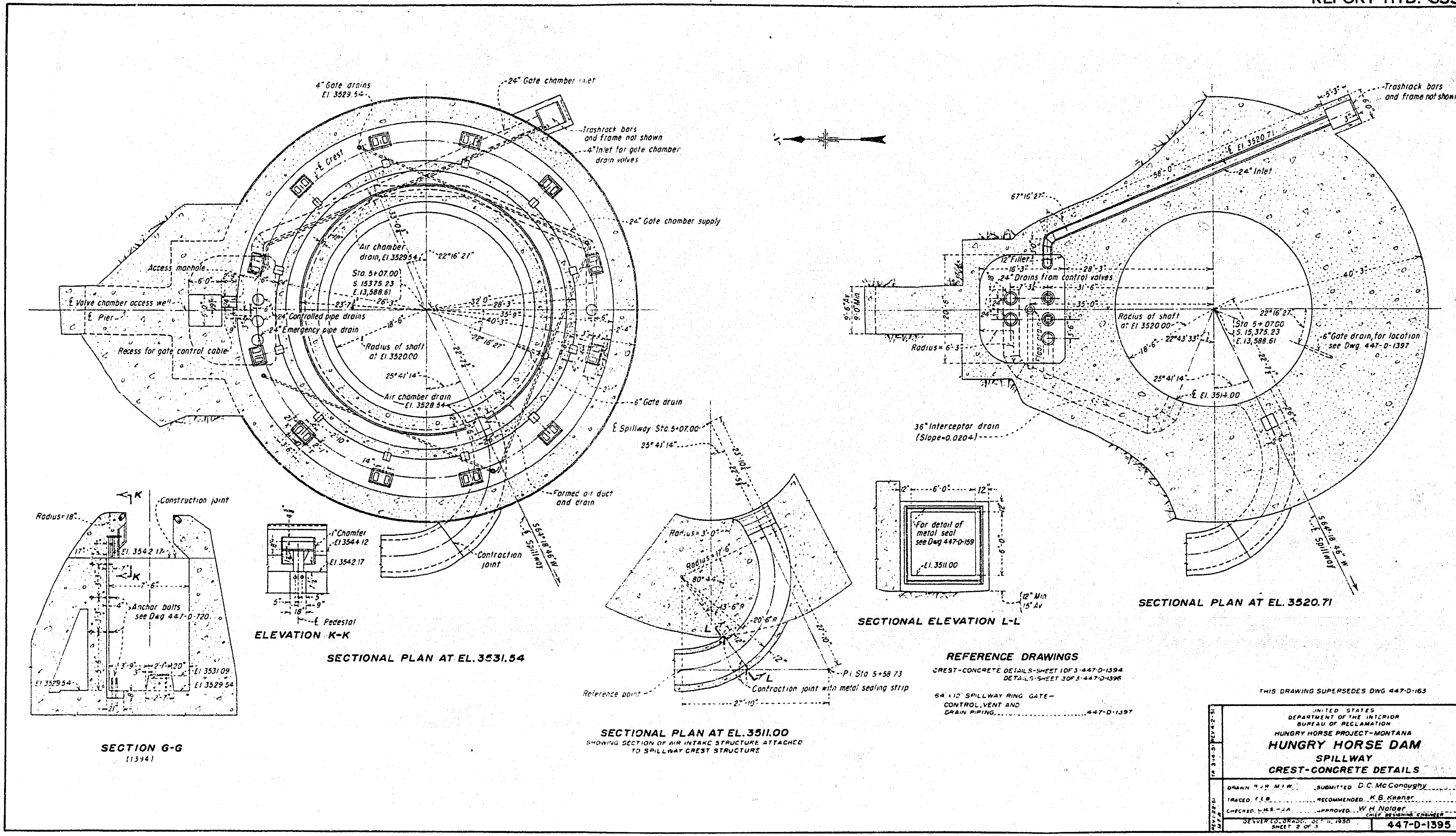
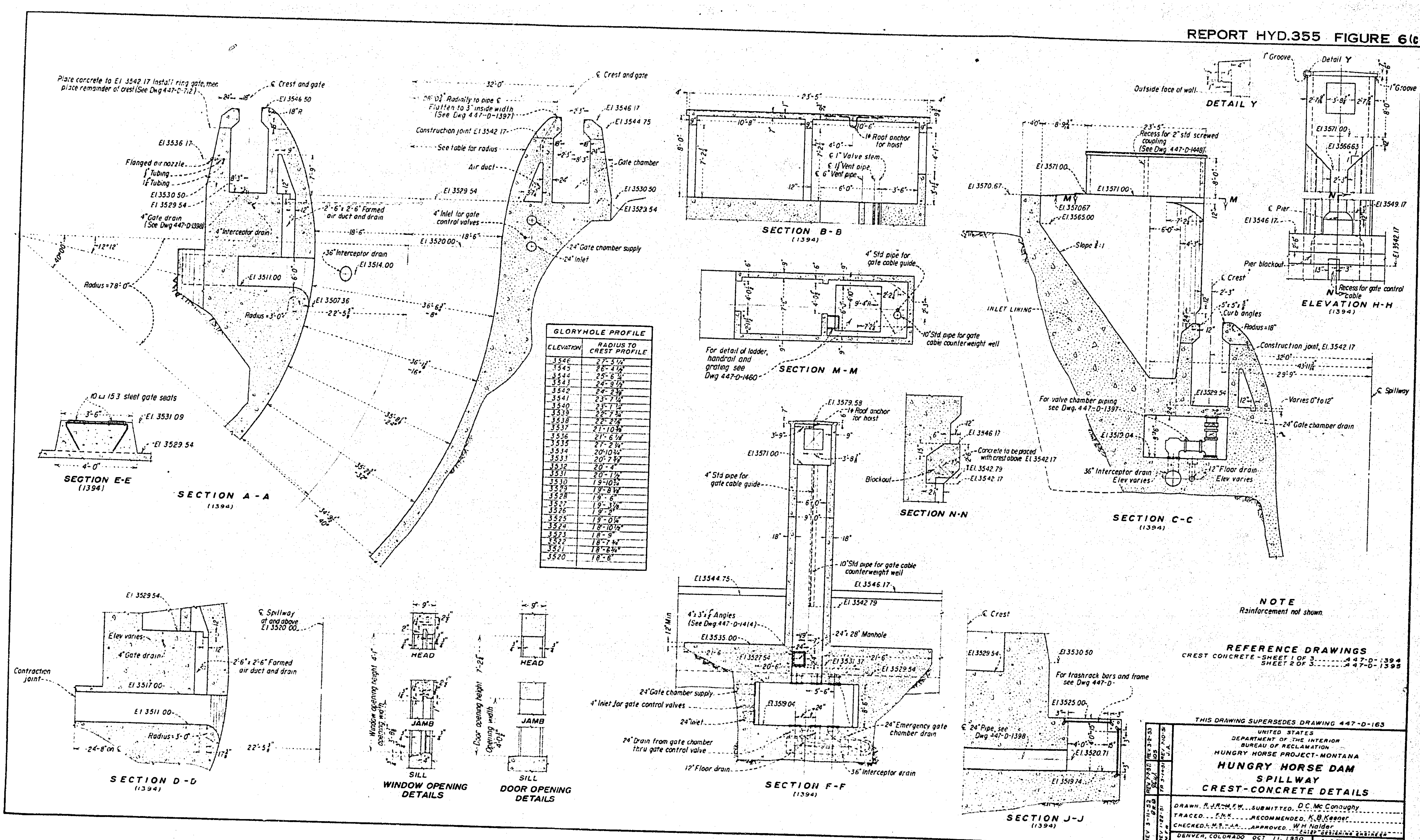

SECTIONAL ELEVATION P-P
SECTION W-W
SECTION Q-Q
SECTION R-R
PLAN
GATE NOT SHOWN
NOTE
Reinforcement not shown. For reinforcement details see Dwgs. 447-D-1496 and 1497
REFERENCE DRAWINGS
CREST-CONCRETE DETAILS SHEET 2 OF 3...447-D-1395
CREST-CONCRETE DETAILS SHEET 3 OF 3...447-D-1396
64'x12' RING GATE ASSEMBLY.........447-D-712
INLET EXCAVATION-PLAN AND SECTIONS....447-D-1031
THIS DRAWING SUPERSEDES DWG. 447-D-163
UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
HUNGRY HORSE PROJECT-MONTANA
HUNGRY HORSE DAM
SPILLWAY
CREST-CONCRETE DETAILS
SUBMITTED D.C. McConaughy
RECOMMENDED K.B. Keener
APPROVED W.H. Nalder
DENVER, COLORADO, OCTOBER 11, 1950
SHEET 1 OF 3
447-D-1394
RECORD DRAWING

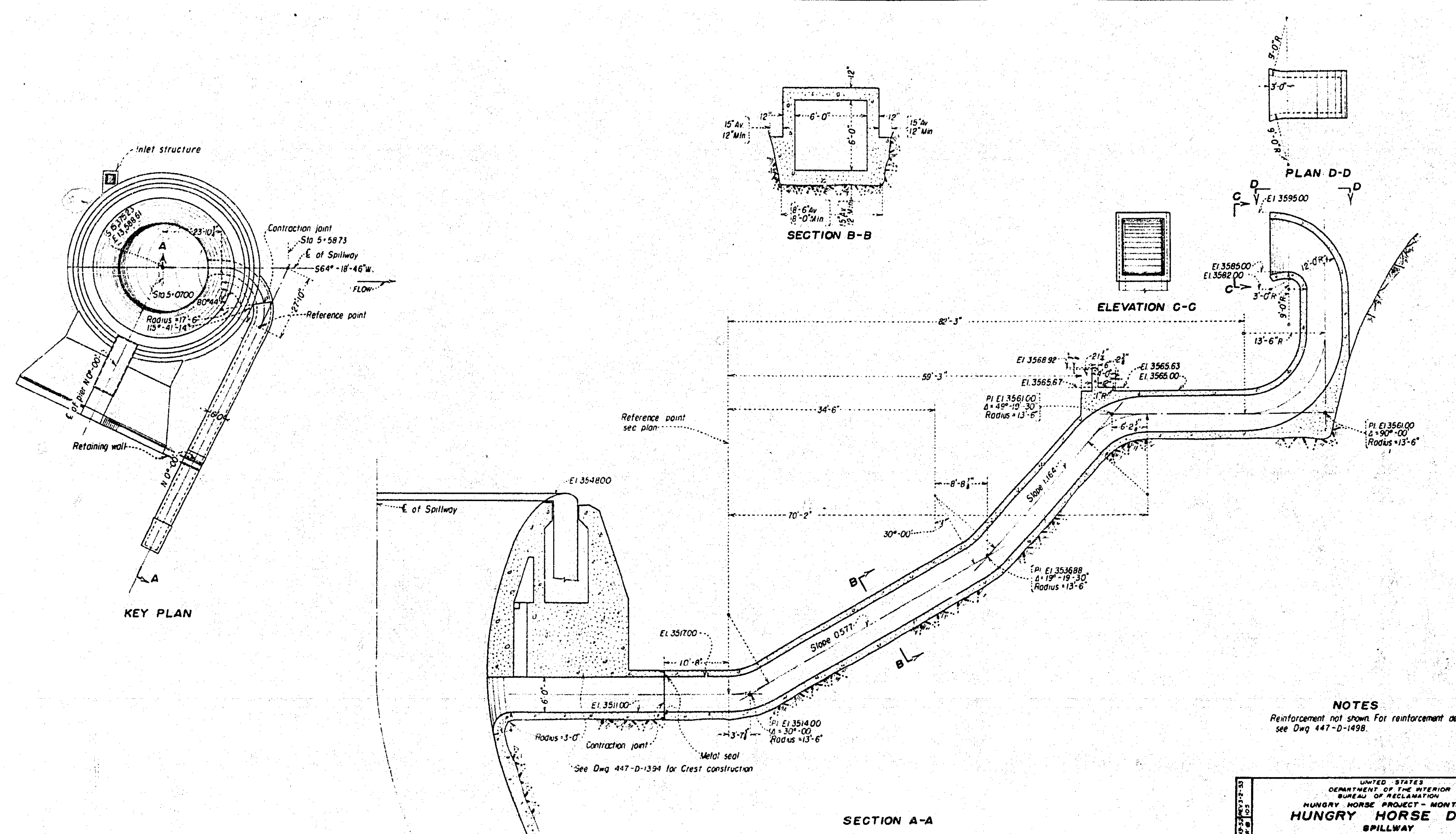
FIGURE 6(b)
REPORT HYD. 355





GLORYHOLE PROFILE

ELEVATION	RADIUS TO CREST PROFILE
3546	27'-5¼"
3545	26'-4½"
3544	25'-6¼"
3543	24'-9½"
3542	24'-2⅜"
3541	23'-7¼"
3540	23'-1¼"
3539	22'-7¾"
3538	22'-2⅞"
3537	21'-10⅜"
3536	21'-6⅛"
3535	21'-2¼"
3534	20'-10¾"
3533	20'-7⅛"
3532	20'-4"
3531	20'-1½"
3530	19'-10¾"
3529	19'-8⅛"
3528	19'-6"
3527	19'-3⅞"
3526	19'-2"
3525	19'-0¼"
3524	18'-10½"
3523	18'-9"
3522	18'-7¾"
3521	18'-6¾"
3520	18'-6"



NOTES

Reinforcement not shown. For reinforcement details see Dwg 447-D-1498.

UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
HUNGRY HORSE PROJECT - MONTANA

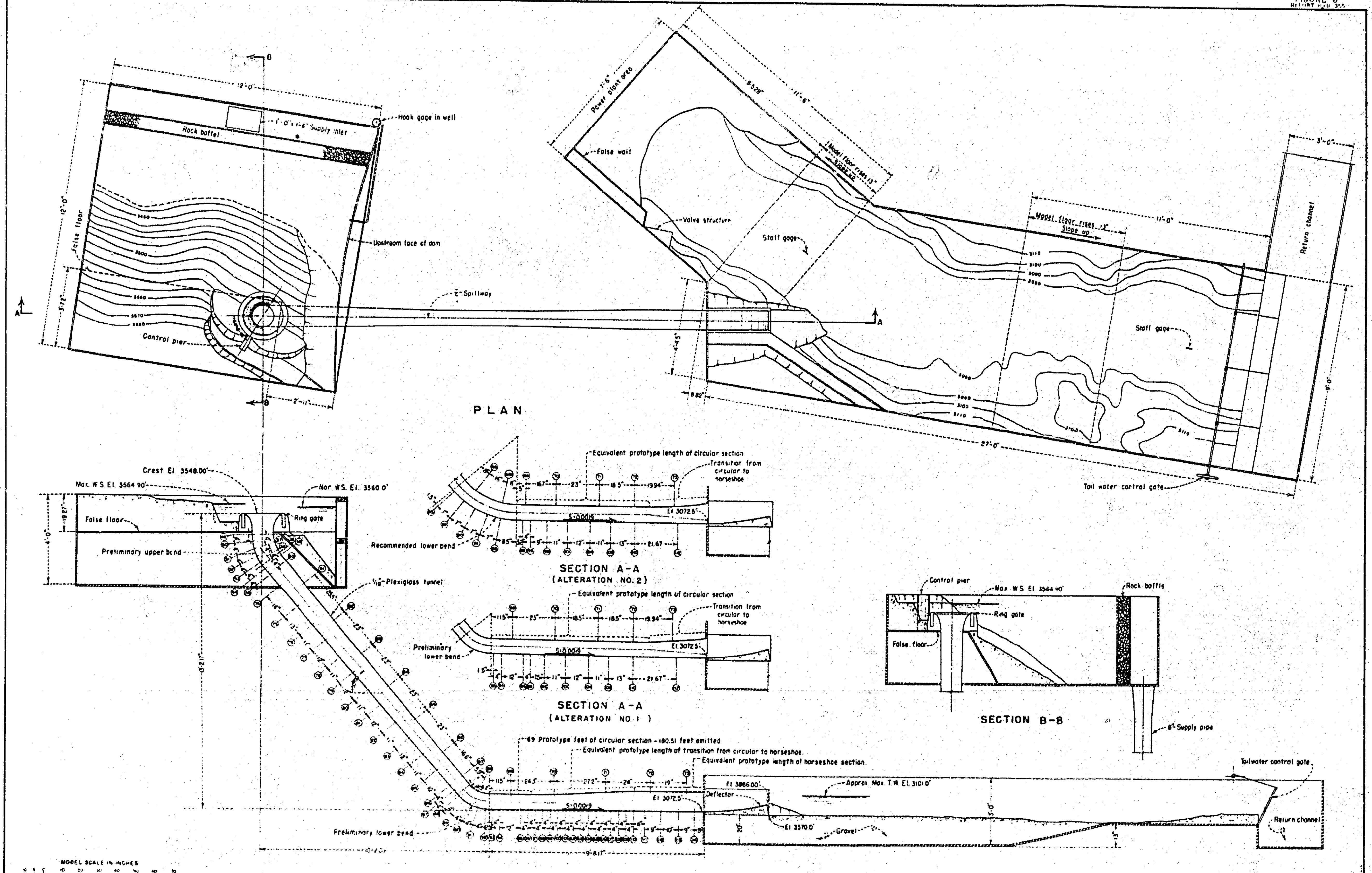
HUNGRY HORSE DAM
SPILLWAY
AIR INTAKE STRUCTURE
CONCRETE DETAILS

DRAWN ... M.F.H. ... SUBMITTED ... Paul K. Bock
TRACED ... R.A.G. ... RECOMMENDED ... D.C. Mc Conaughy
CHECKED ... P.K.B. & J.A. ... APPROVED ... K.B. Keener
DENVER, COLORADO. FEB. 26, 1951

447-D-1499

RECORD DRAWING

FIGURE 8



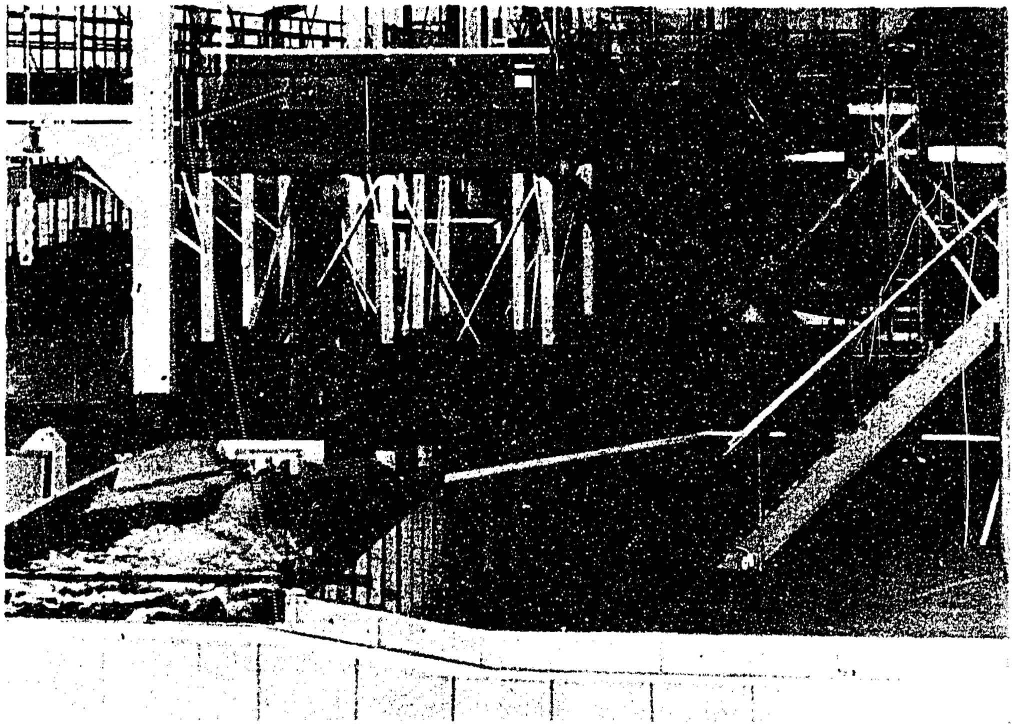
NOTE: Circled numbers designate piezometers

SECTION A-A

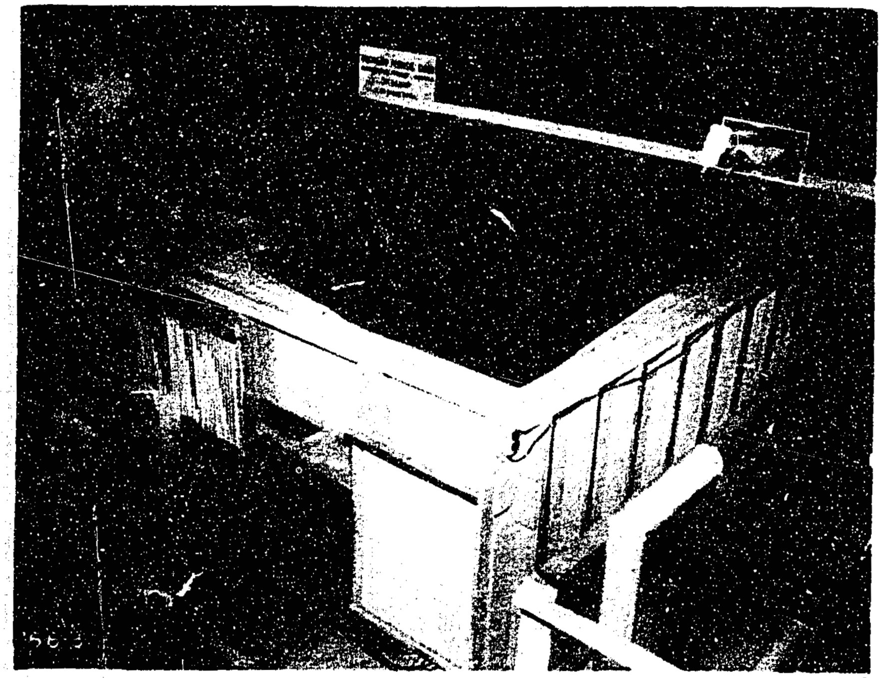
HUNGRY HORSE DAM SPILLWAY

MODEL LAYOUT

1:36 MODEL

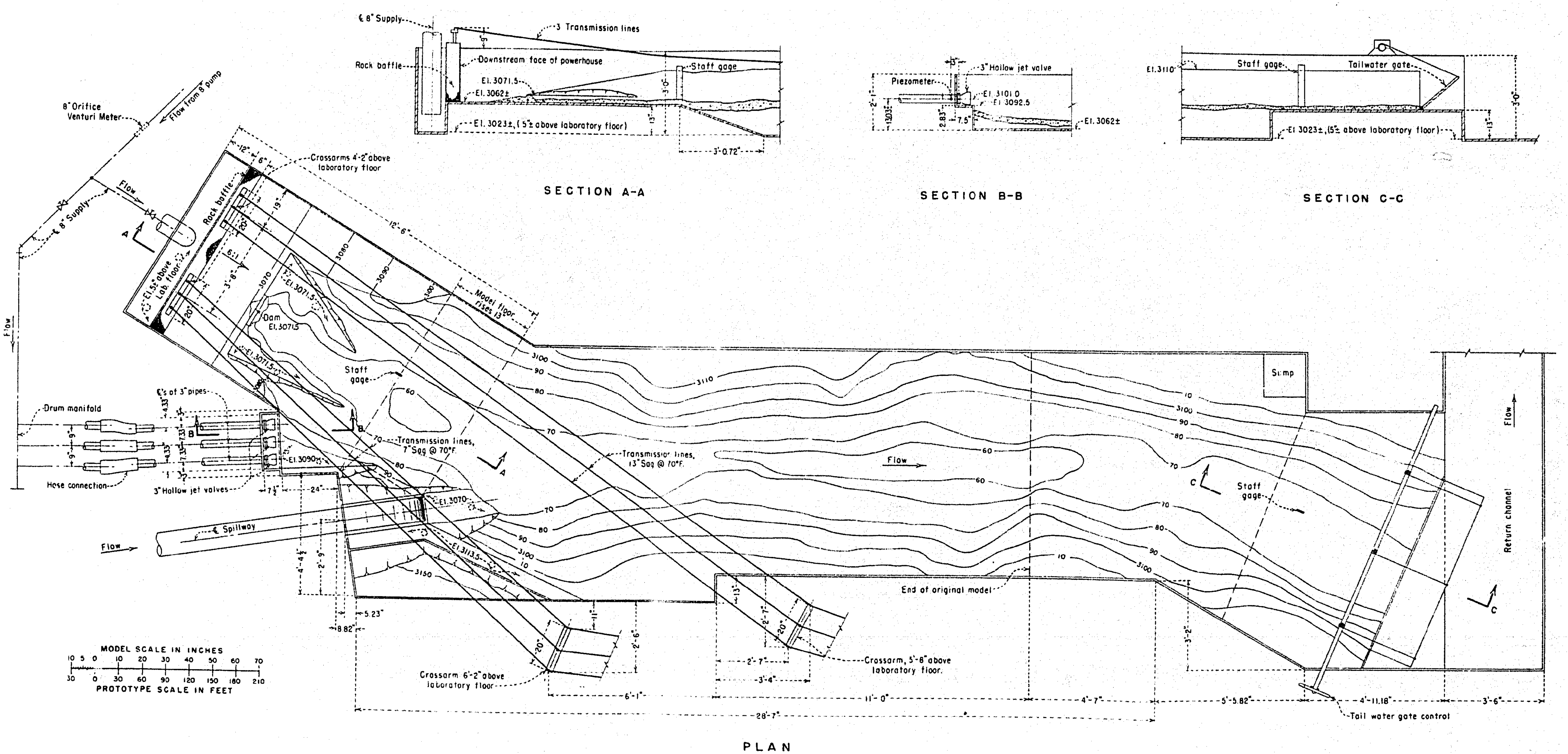


(a) Tunnel and downstream river area.

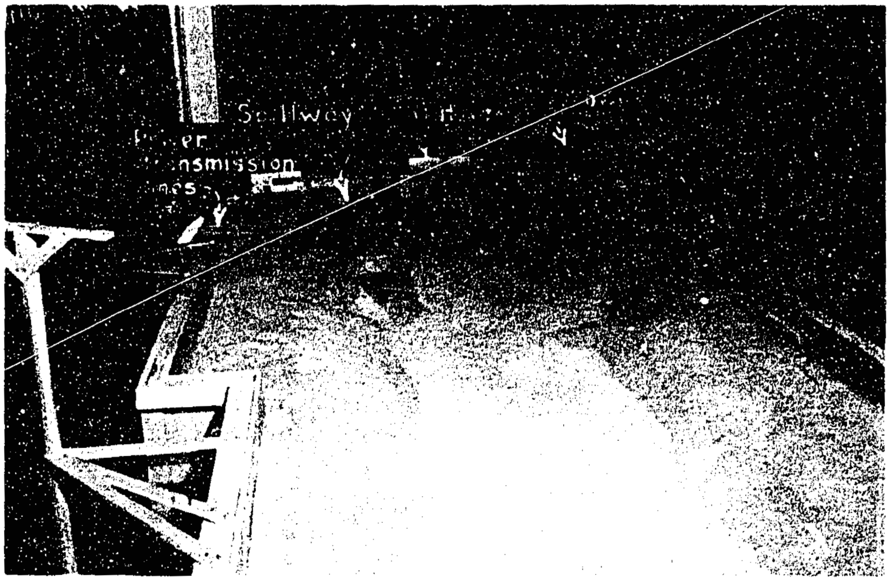


(b) Reservoir area.

HUNGRY HORSE DAM SPILLWAY
Model Discharging Maximum Design Flow--53,000 Second-feet
1:36 Model



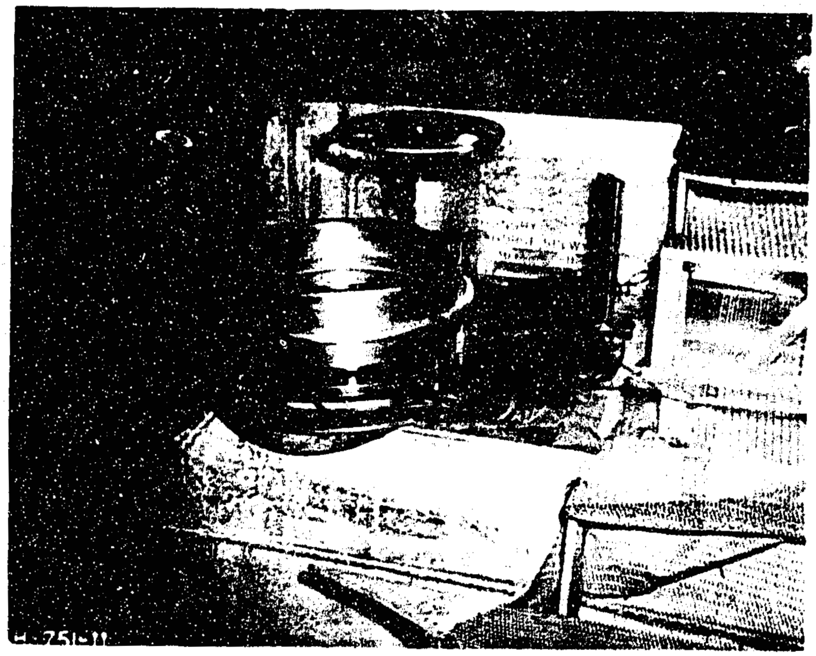
HUNGRY HORSE DAM SPILLWAY
MODEL REVISED LAYOUT OF THE DOWNSTREAM RIVER AREA
1:36 MODEL



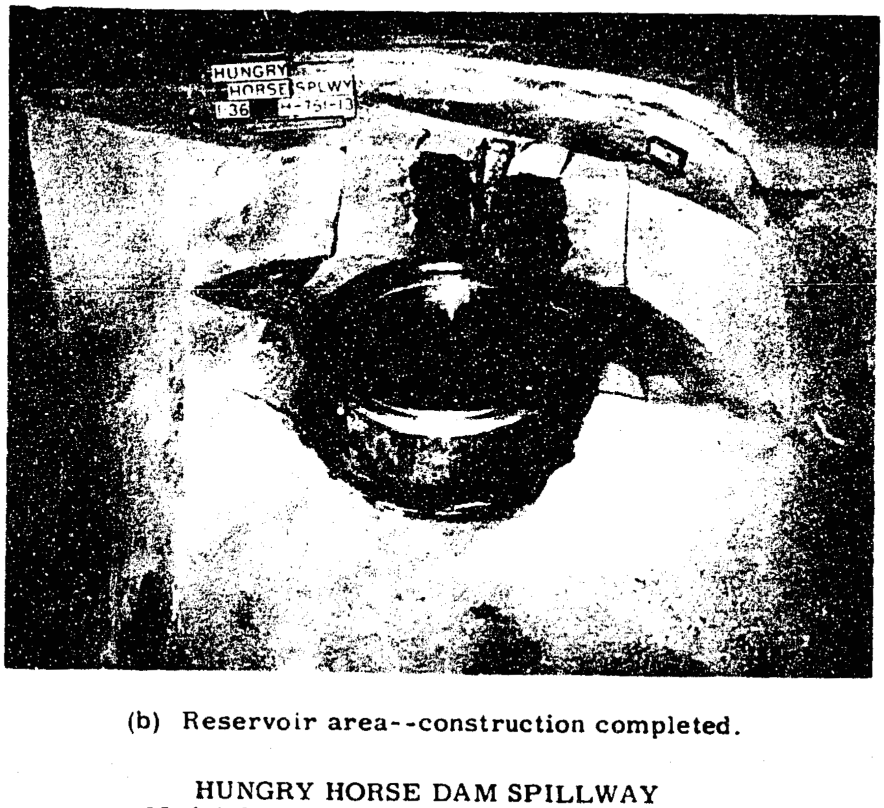
(a) Looking upstream showing transmission lines from powerhouse to transmission towers--preliminary location.

(b) Powerhouse, 11,000 second-feet--outlets, 15,000 second-feet--spillway, 10,000 second-feet.

HUNGRY HORSE DAM SPILLWAY
Views of the Revised Model of the Downstream River Area
1:36 Model

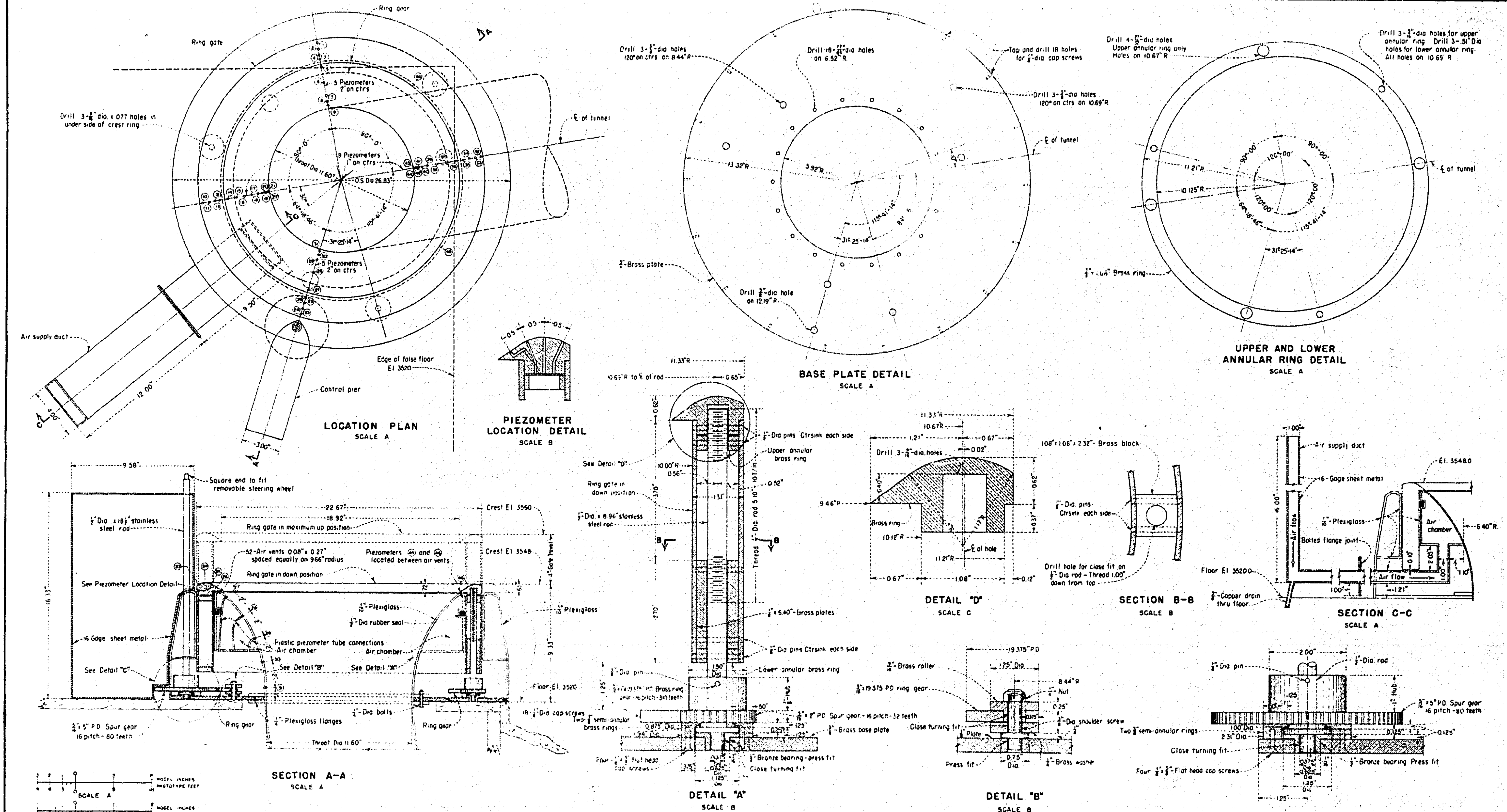


(a) Reservoir area during construction showing morning-glory, ring gate, control pier, air supply duct, and piezometer tubes.



(b) Reservoir area--construction completed.

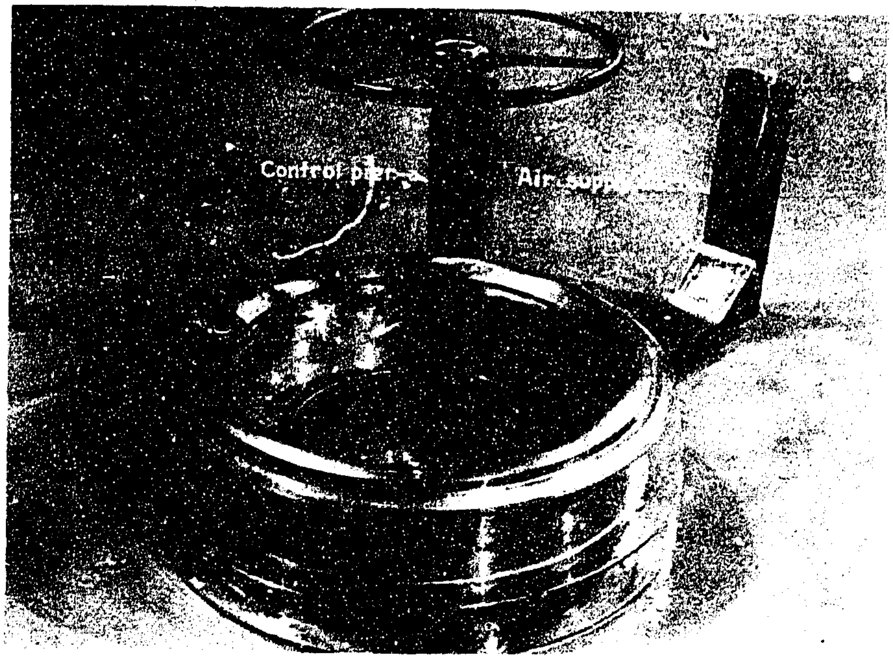
HUNGRY HORSE DAM SPILLWAY
Model Construction of the Reservoir Area
1:36 Model

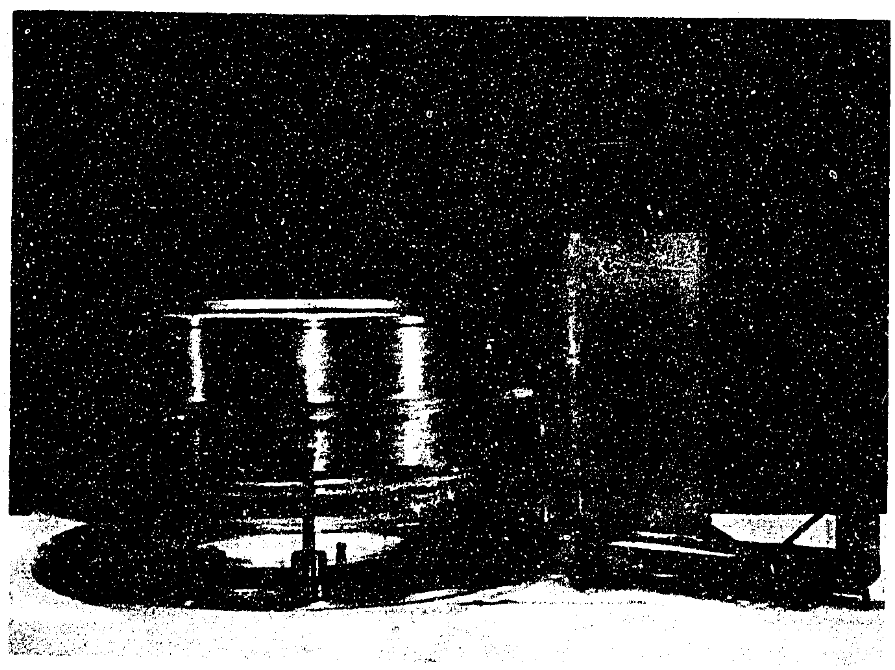


HUNGRY HORSE DAM SPILLWAY

MODEL OF THE PRELIMINARY MORNING-GLORY, RING GATE, AND VENTING SYSTEM--
PLAN, SECTIONS AND DETAILS

1:36 MODEL

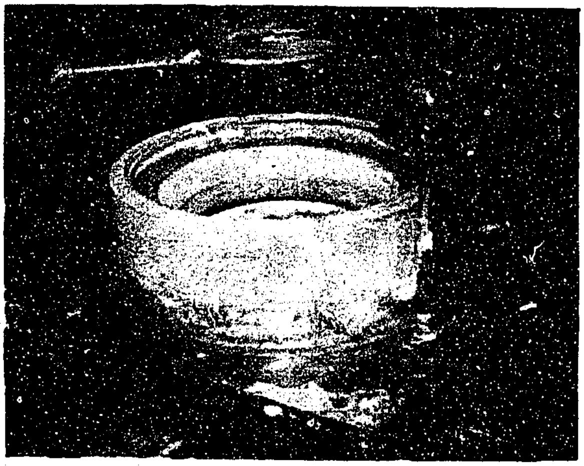




HUNGRY HORSE DAM SPILLWAY
Model Views of the Preliminary Morning-Glory Ring Gate,
Control Pier, and Air Duct
1:36 Model

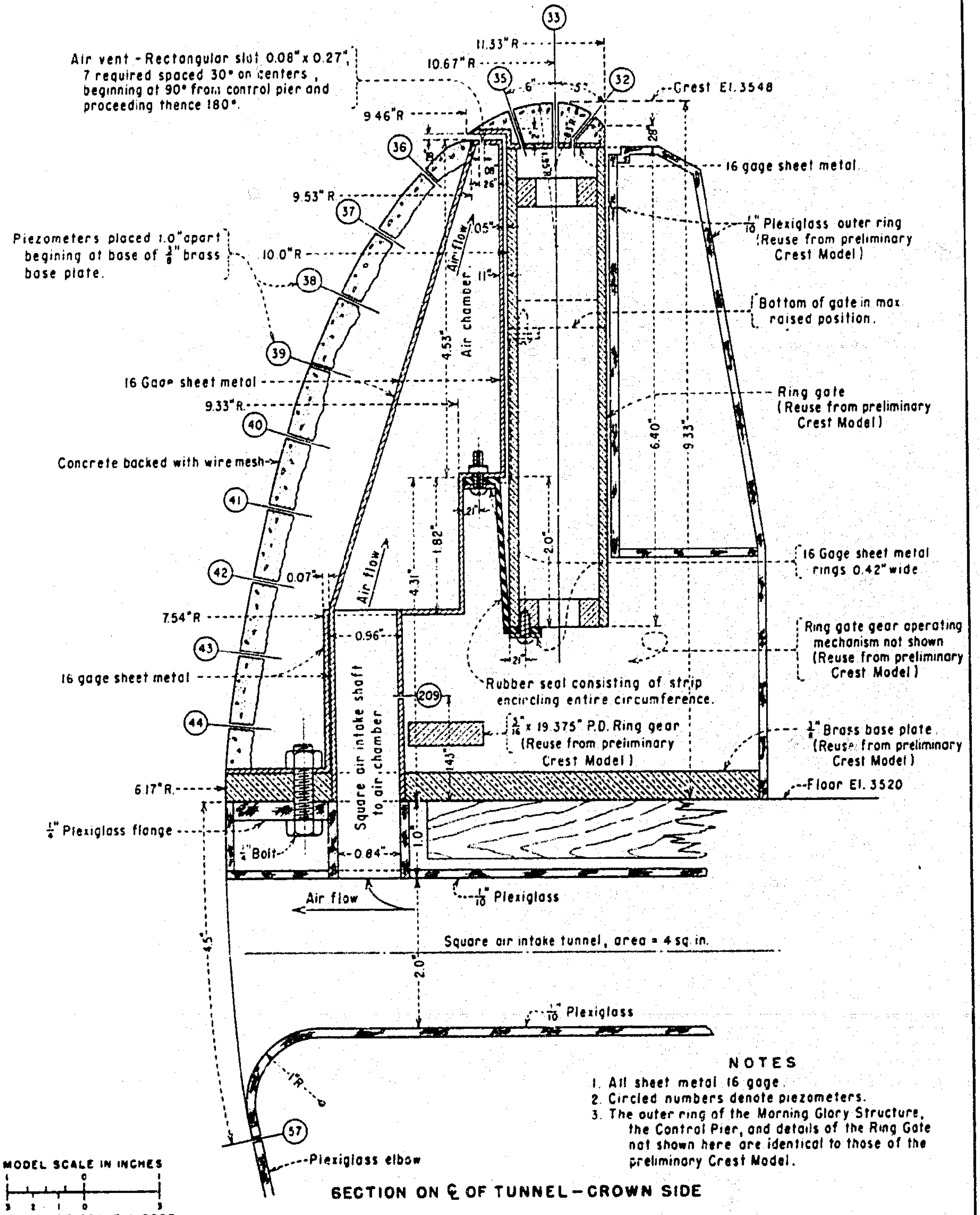
Figure 15
Report Hyd 355

(a) During construction showing revolving template used to form spillway shape.



(b) Construction completed.

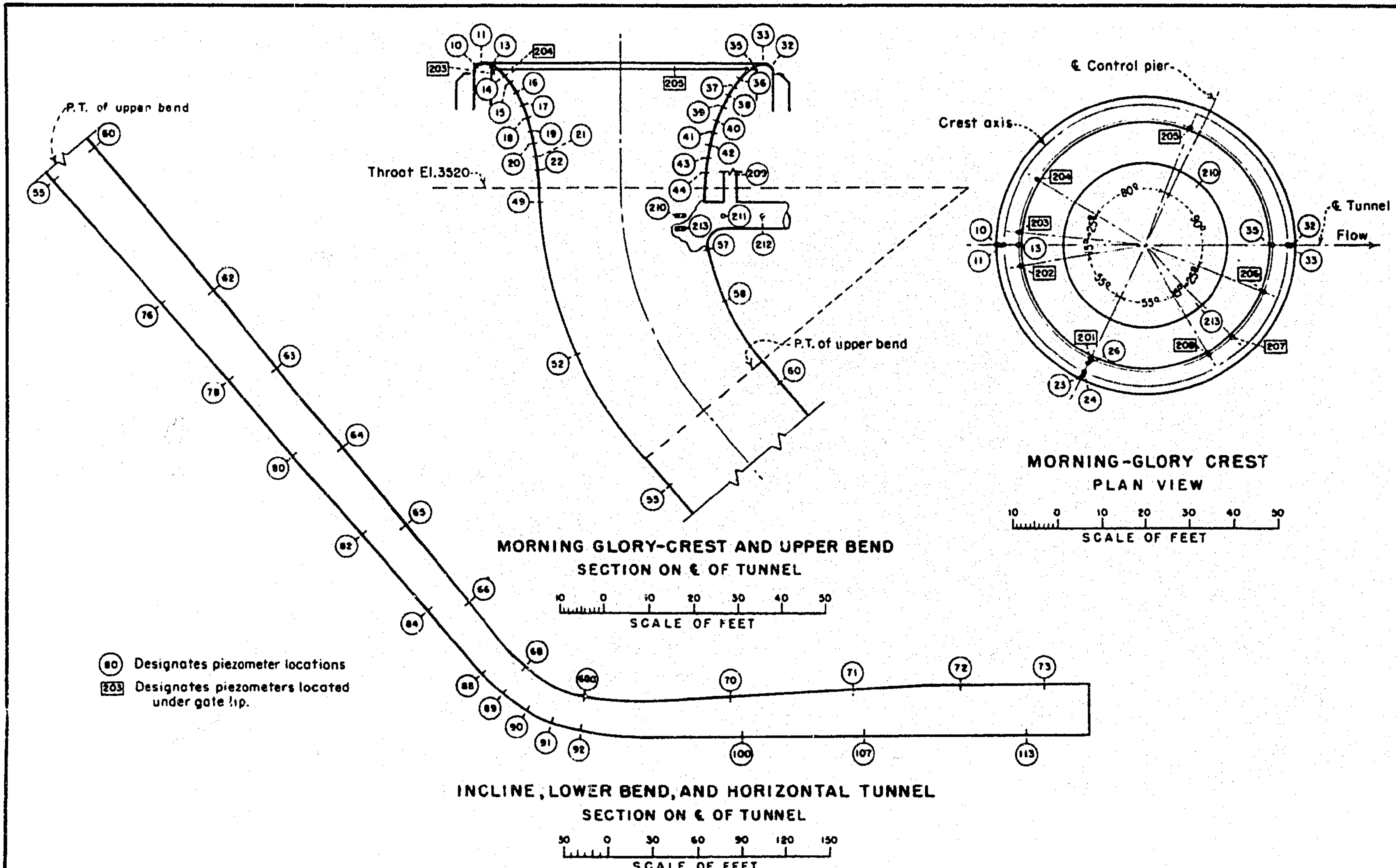
HUNGRY HORSE DAM SPILLWAY
Model Construction of Second Morning-Glory
1:36 Model



NOTES
1. All sheet metal 16 gage.
2. Circled numbers denote piezometers.
3. The outer ring of the Morning Glory Structure, the Control Pier, and details of the Ring Gate not shown here are identical to those of the preliminary Crest Model.

SECTION ON ℄ OF TUNNEL—CROWN SIDE

HUNGRY HORSE DAM SPILLWAY
MODEL OF
THE RECOMMENDED MORNING-GLORY CREST, RING GATE AND VENTING SYSTEM
1:36 MODEL

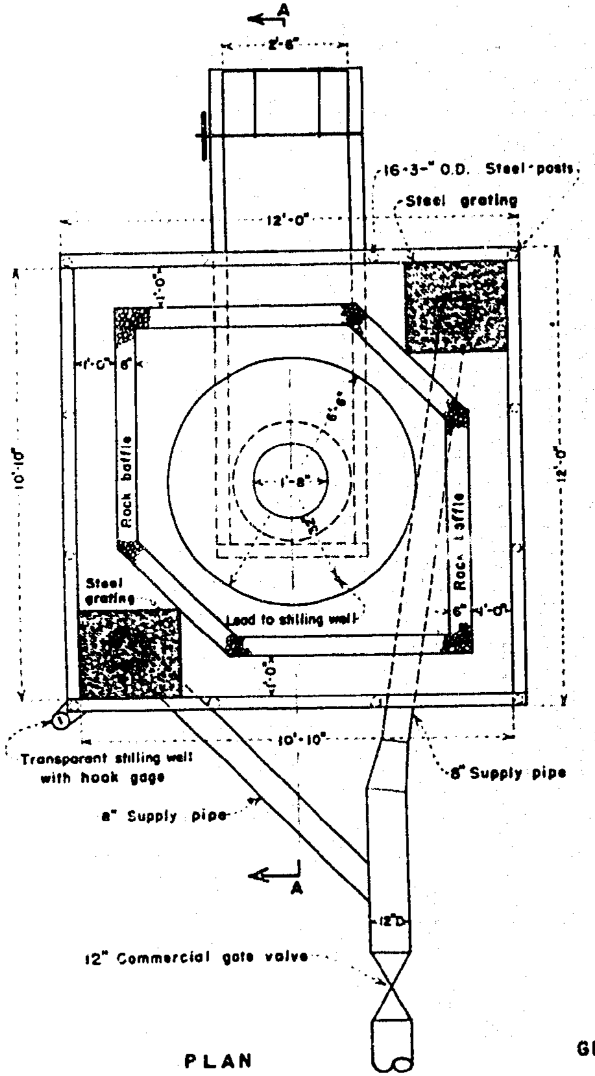


HUNGRY HORSE DAM SPILLWAY

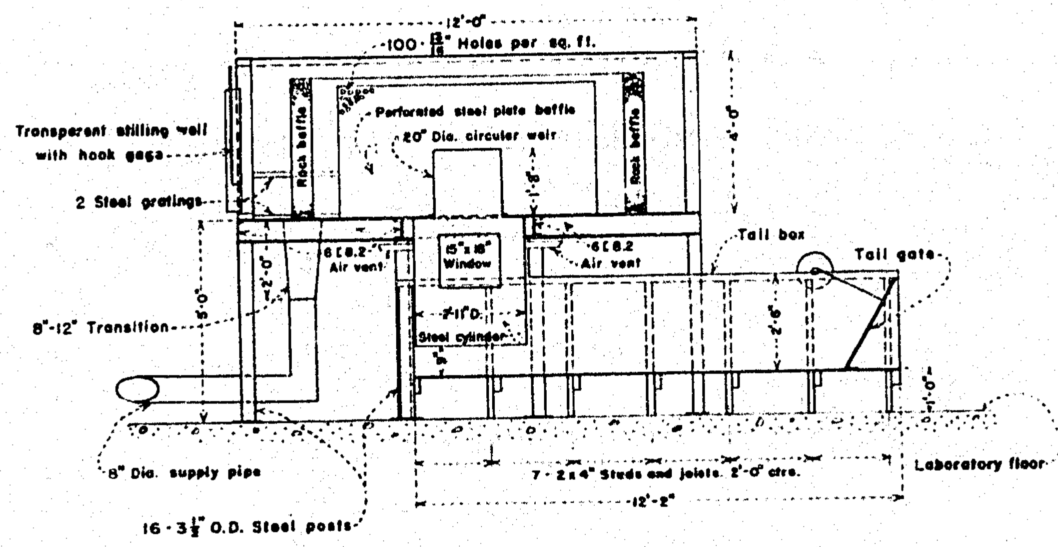
PIEZOMETER LOCATIONS IN THE RECOMMENDED SPILLWAY MODEL

1:36 MODEL

262



PLAN



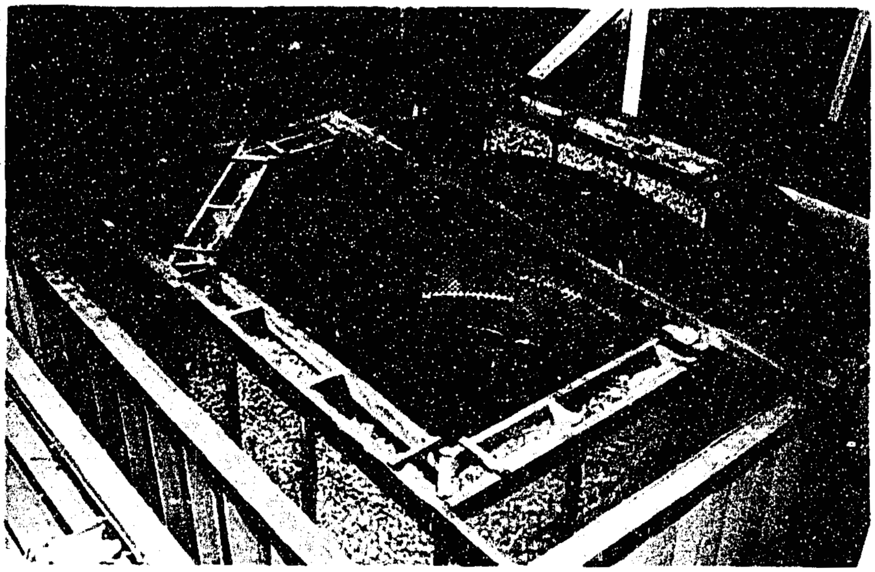
SECTION A-A

HUNGRY HORSE DAM SPILLWAY

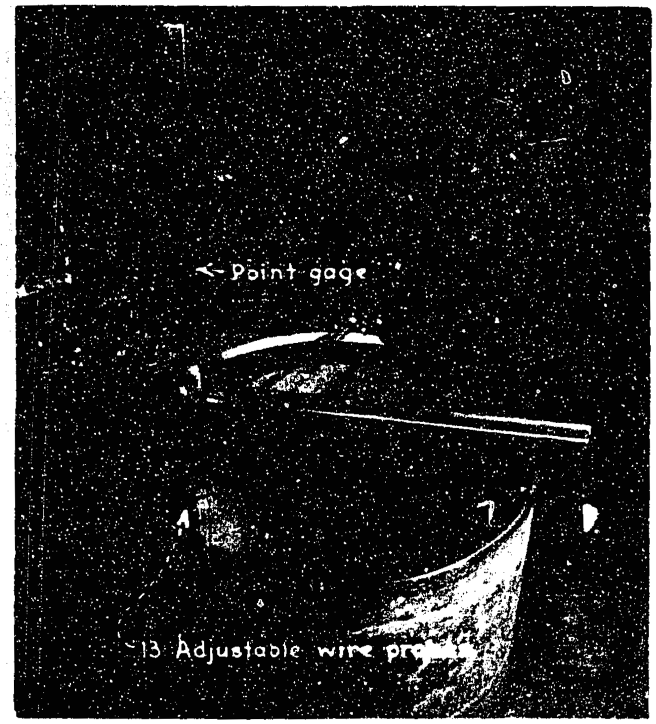
GENERAL LAYOUT OF CIRCULAR WEIR MODEL

1:40.94 MODEL

FIGURE 18
REPORT HYD 355

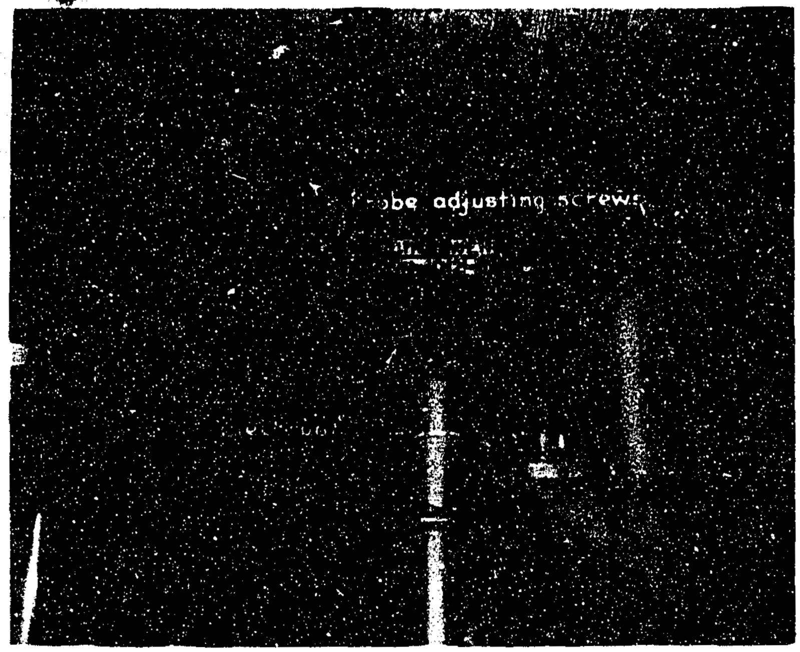


(a) Head box containing circular weir. Note baffle arrangement.

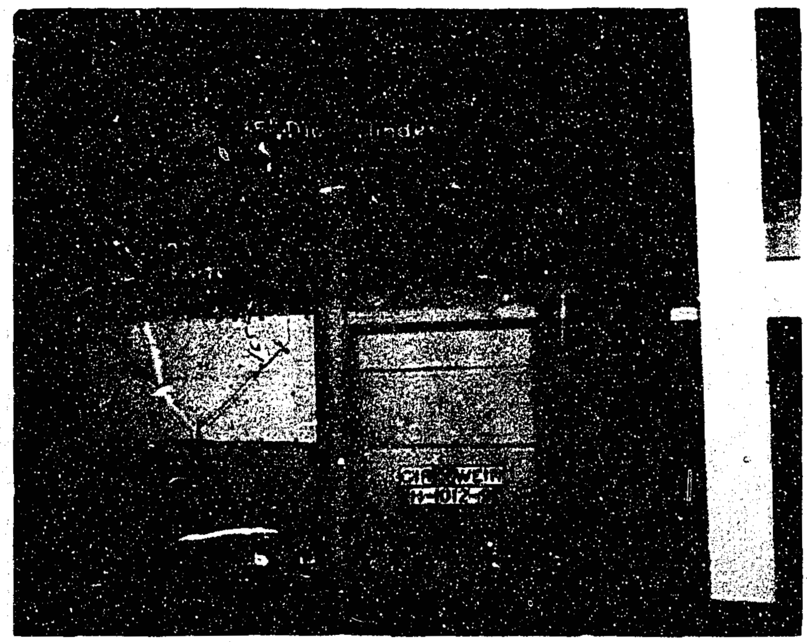


(b) Special point gage for measuring coordinates of probe ends used in determining the undernappe profile.

HUNGRY HORSE DAM SPILLWAY
Circular Weir Head Box and Test Equipment
1:40.94 Model

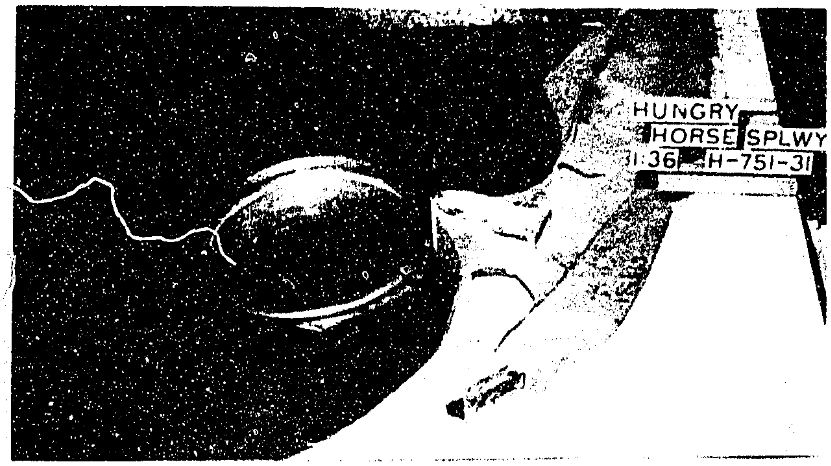


(a) Electronic equipment used in determining the undernappe profile.

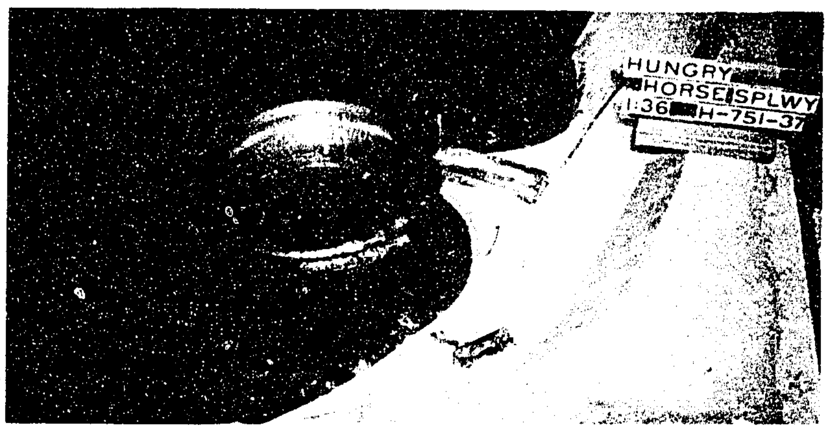


(b) Tailbox, cylinder, vent, and manometer for controlling and measuring the pressure under the profile nappe.

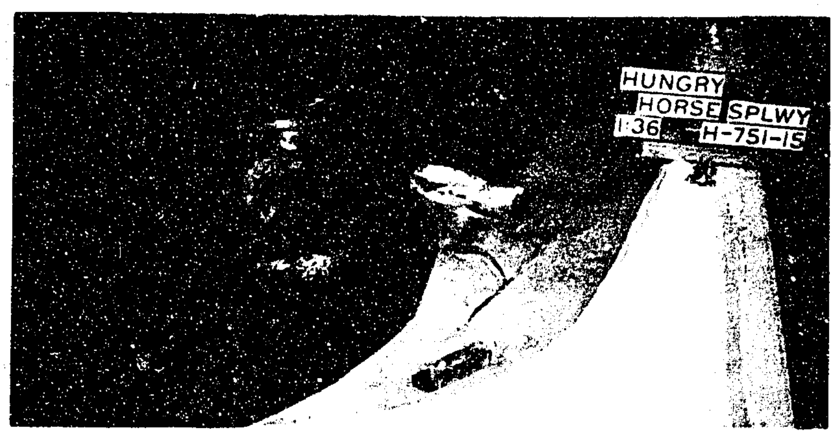
HUNGRY HORSE DAM SPILLWAY
Circular Weir Tail Box and Test Equipment
1:40. 94 Model



(a) 10,000 second-feet.

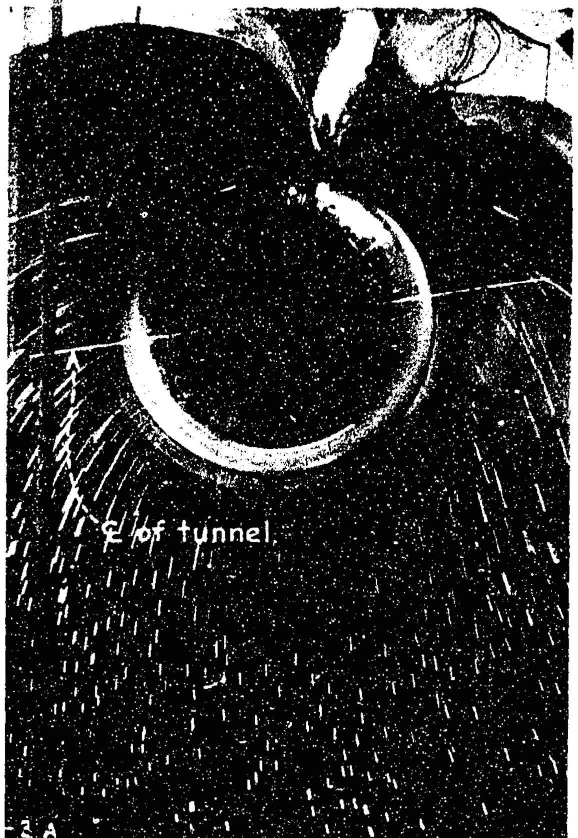


(b) 30,000 second-feet
Note: Rock on the approach bottom had no effect on flow pattern.

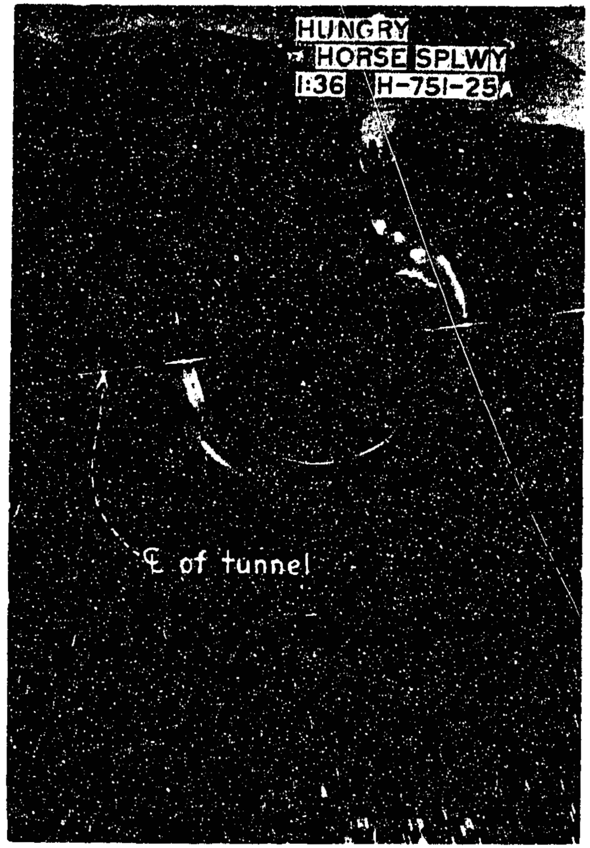


(c) Maximum discharge--53,000 second-feet.

HUNGRY HORSE DAM SPILLWAY
Flow Entering the Preliminary Morning-Glory--Gate Seated
1:36 Model



(a) 10,000 second-feet

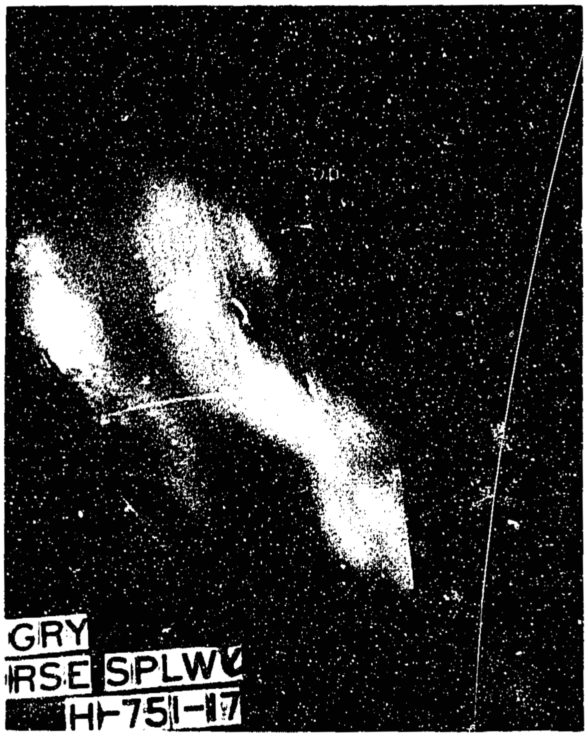


(b) 30,000 second-feet

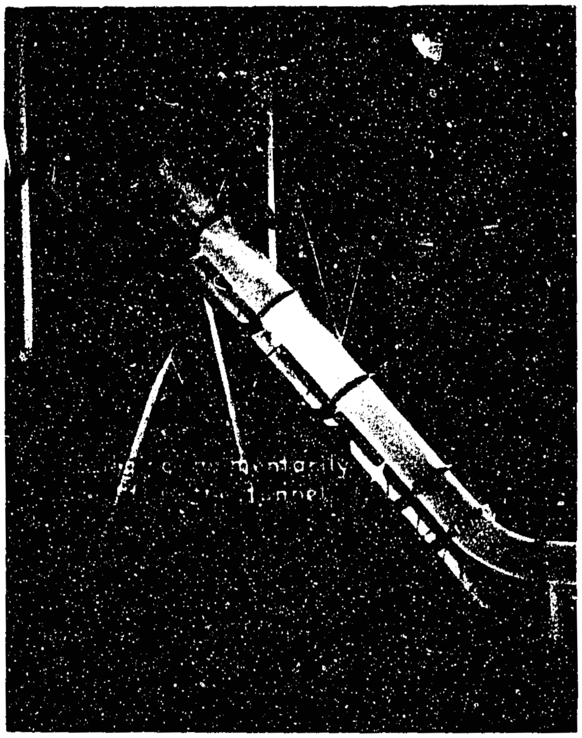
(c) 53,000 second-feet

Note: The bulk of the flow enters the spillway from in front of the control pier which causes a zigzag flow pattern through the tunnel.

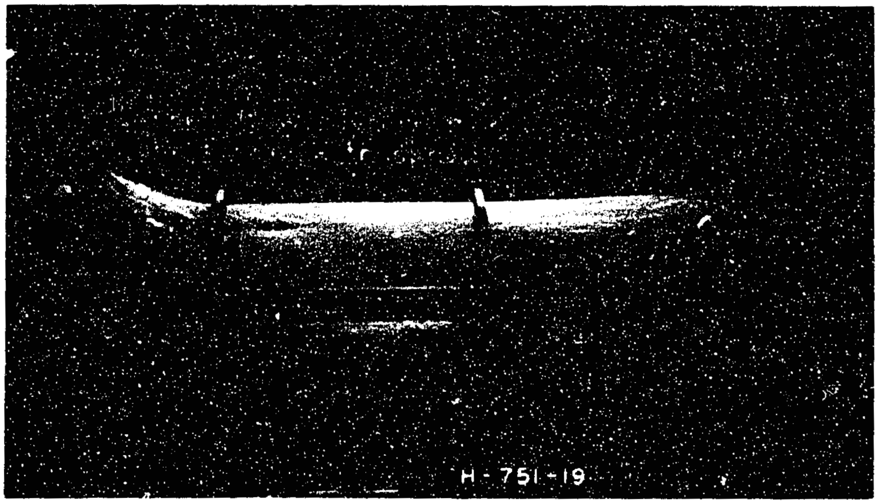
HUNGRY HORSE DAM SPILLWAY
Flow Currents in the Spillway Approach Area--Gate Seated
1:36 Model



(a) Upper bend.



(b) Inclined tunnel.

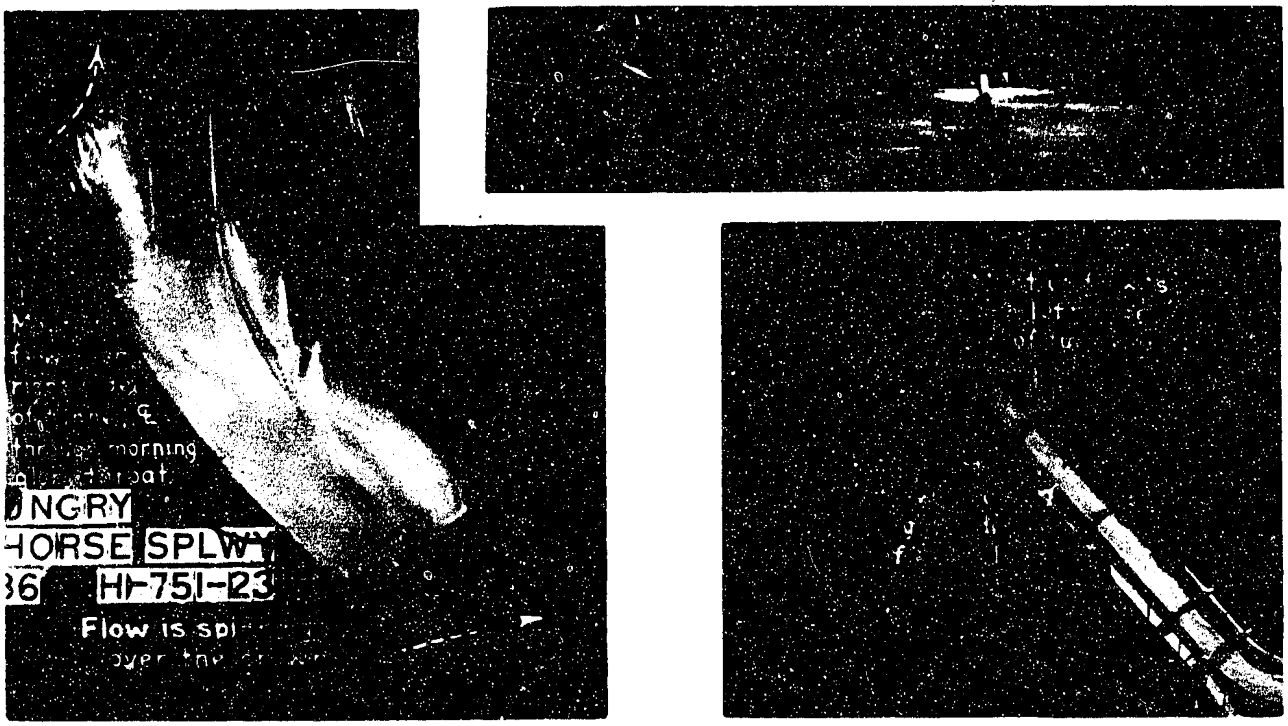


(c) Lower bend and horizontal tunnel.

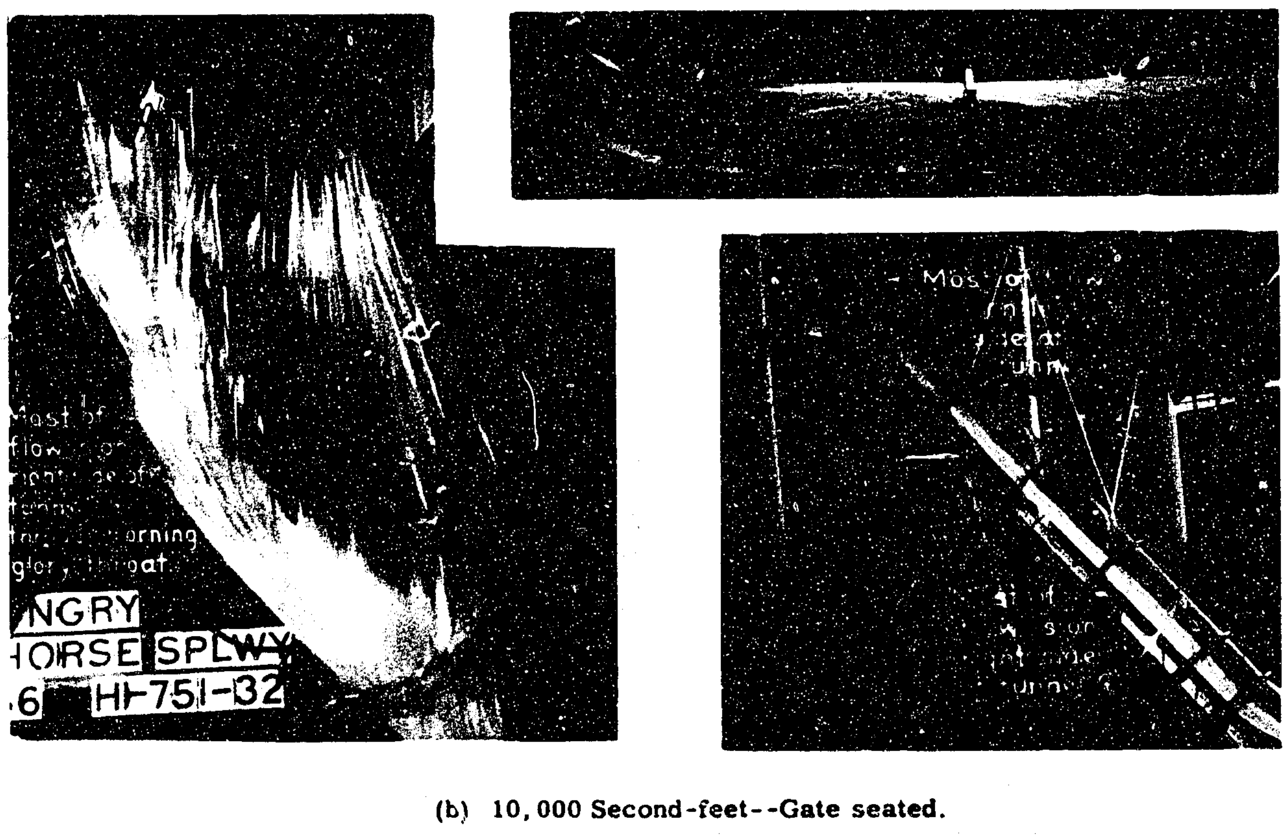
Note: The flow spins and zigzags through the tunnel, but not as much as for smaller discharges.

HUNGRY HORSE DAM SPILLWAY
Preliminary Morning-Glory Spillway Discharging the Maximum Flow of 53,000 Second-Feet
1:36 Model

Figure 24
Report Hyd 355

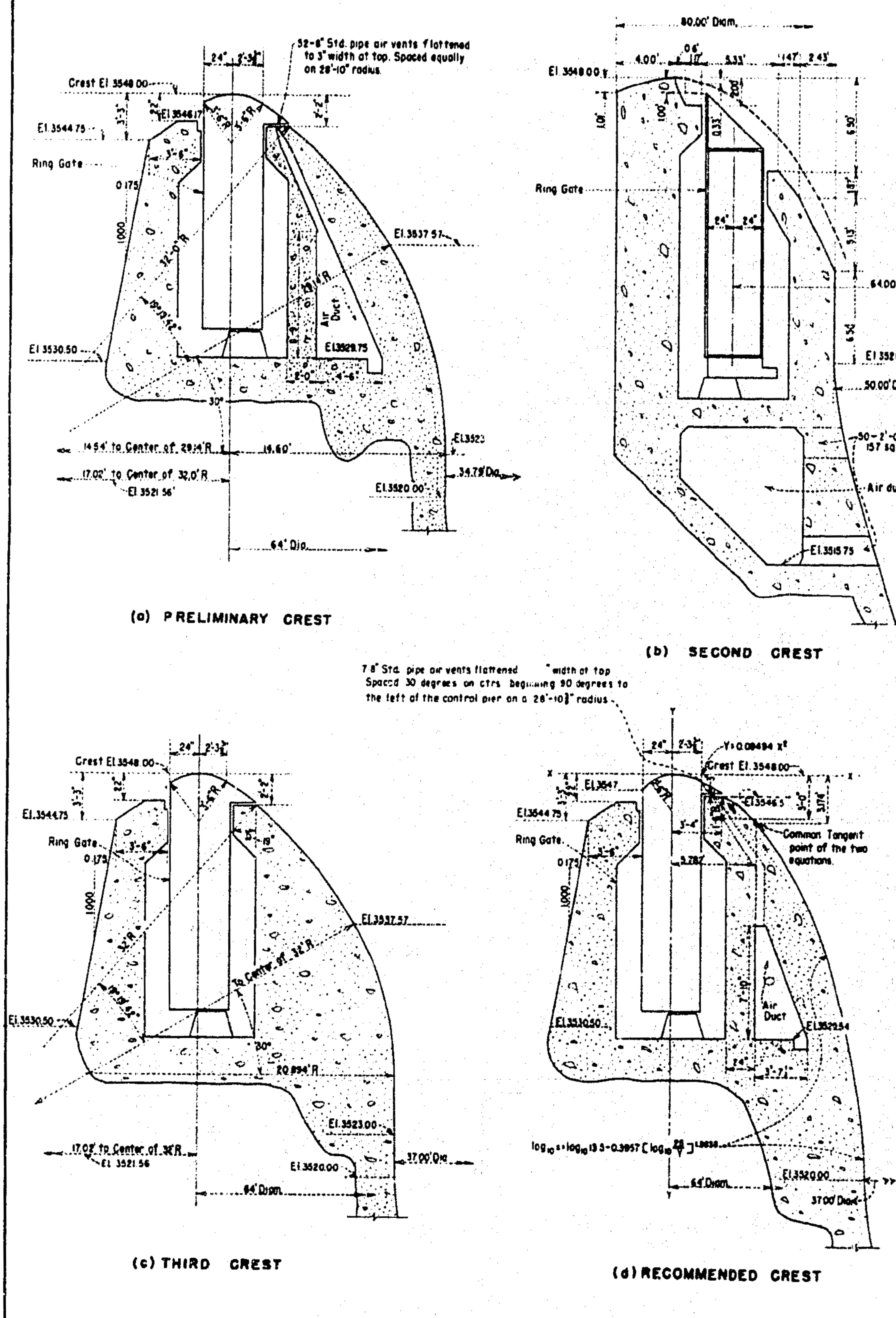


(a) 30,000 Second-feet--Gate seated.



(b) 10,000 Second-feet--Gate seated.

HUNGRY HORSE DAM SPILLWAY
Preliminary Morning-Glory Spillway--30,000 and 10,000 Second-Feet
1:36 Model



GATE CREST PROFILE

$Y = 0.09494\ X^2$

X	Y
0.000	0.000
0.095	1.000
0.380	2.000
0.855	3.000
1.520	4.000
2.374	5.000
3.174	5.782

GLORY HOLE PROFILE

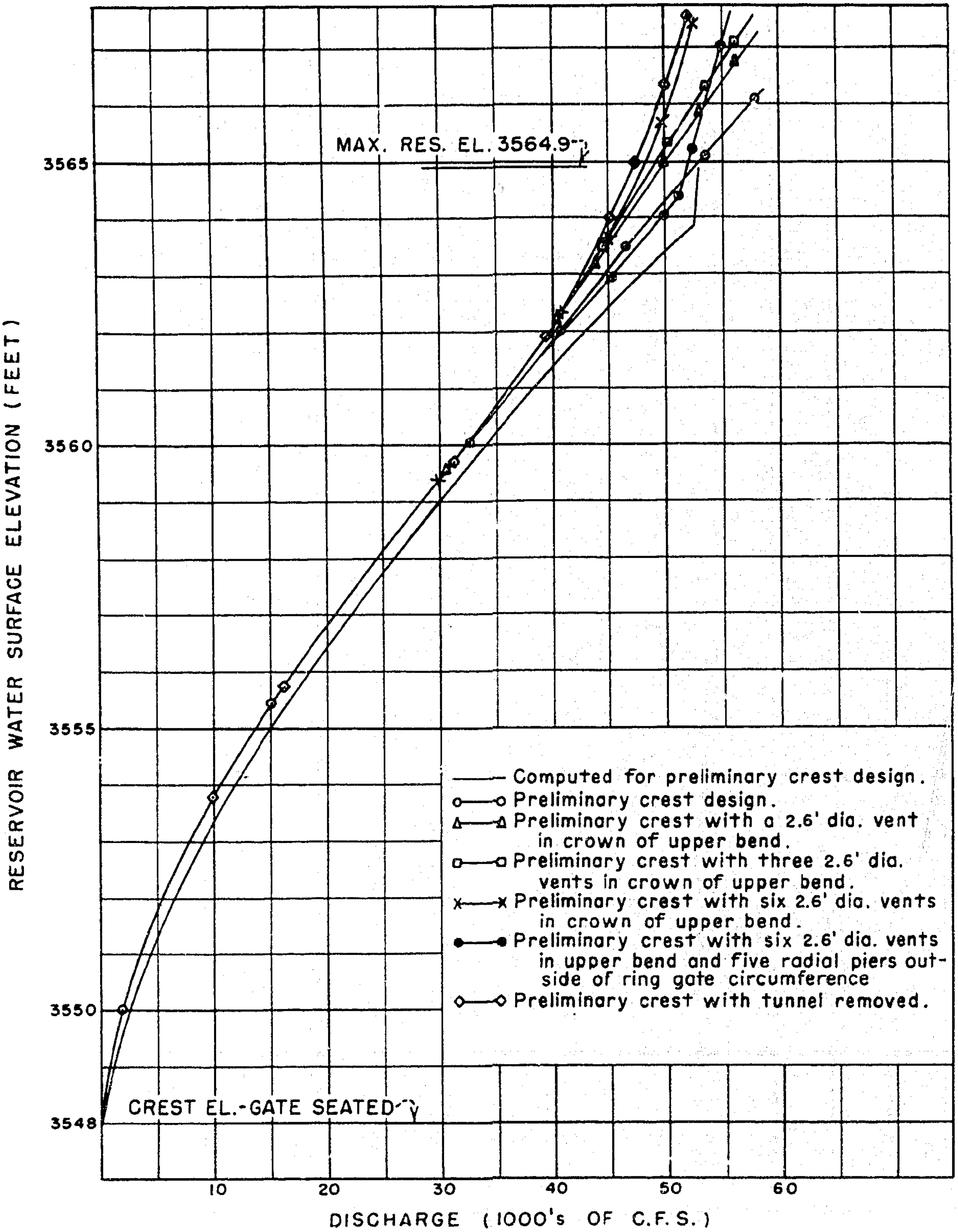
$\log_{10} x = \log_{10} 13.5 - 0.3957 \left[\log_{10} \frac{28}{Y}\right]^{1.2838}$

2	4.559
3	5.620
3.174	5.872
4	6.479
5	7.206
6	7.837
7	8.396
8	8.896
9	9.349
10	9.762
11	10.140
12	10.488
13	10.809
14	11.107
15	11.383
16	11.640
17	11.879
18	12.100
19	12.306
20	12.498
21	12.674
22	12.837
23	12.987
24	13.123
25	13.245
26	13.352
27	13.440
28	13.550

HUNGRY HORSE DAM SPILLWAY

MORNING-GLORY CREST SECTIONS TESTED

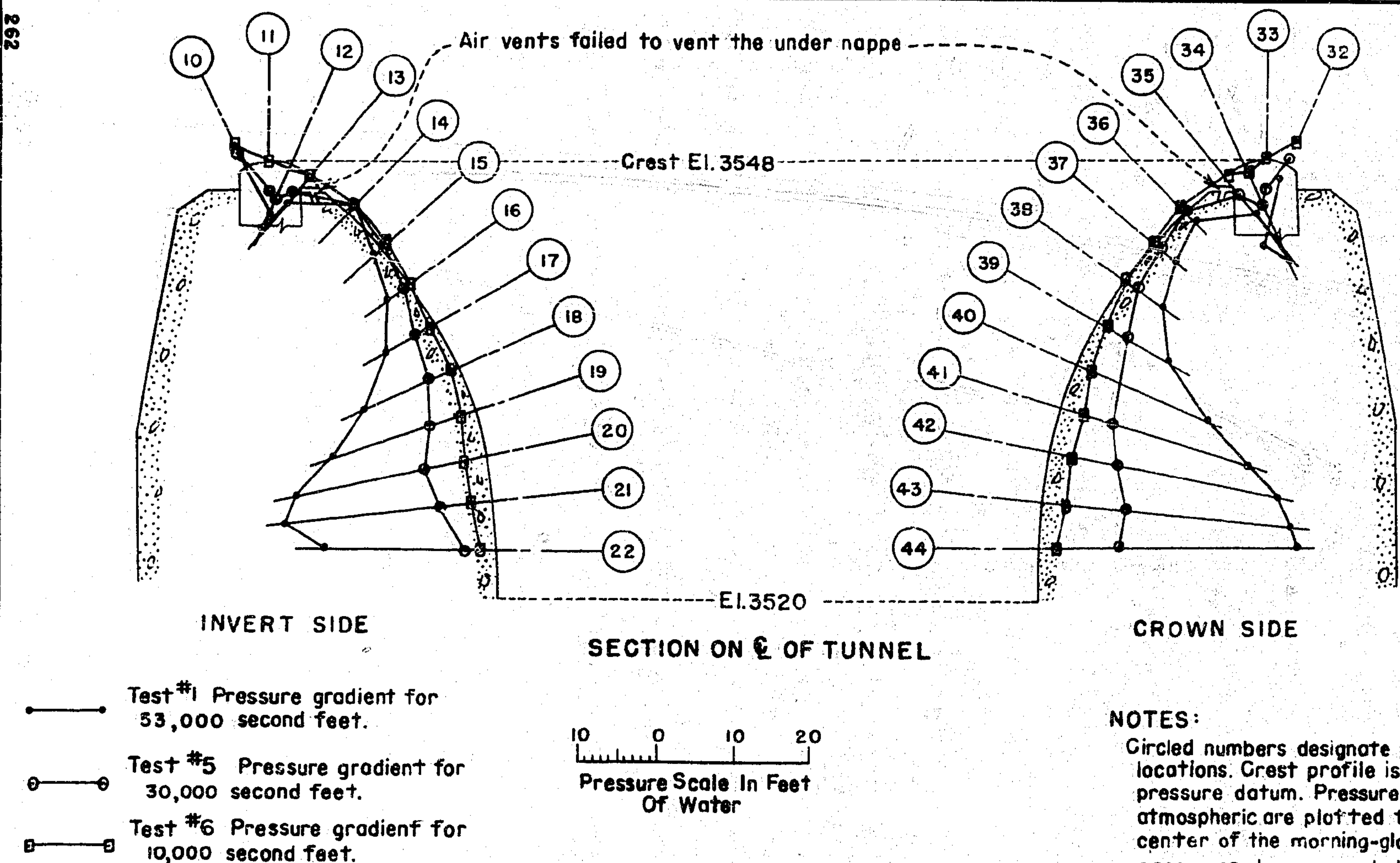
1:36 MODEL



HUNGRY HORSE DAM SPILLWAY

DISCHARGE CURVES

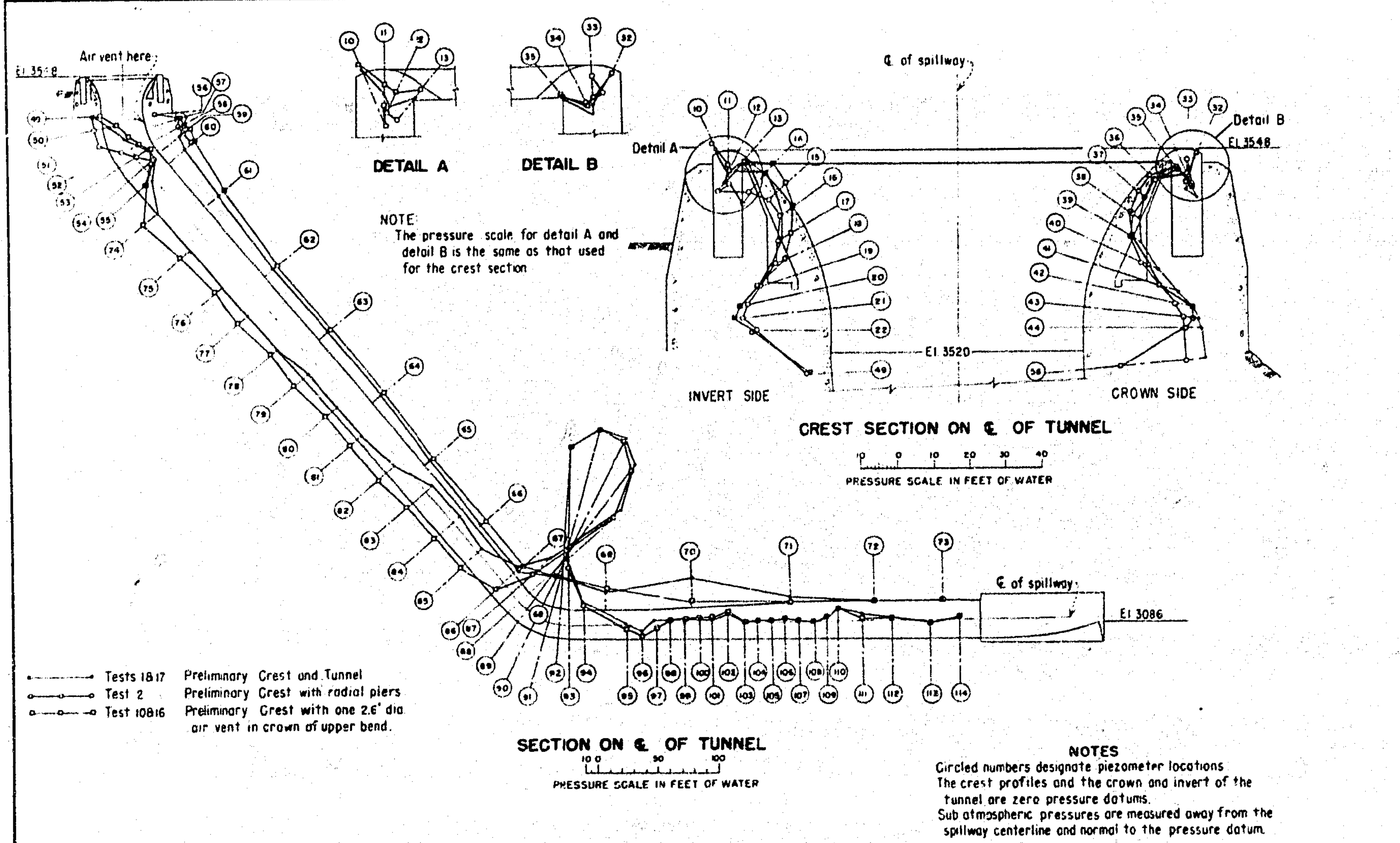
1:36 MODEL



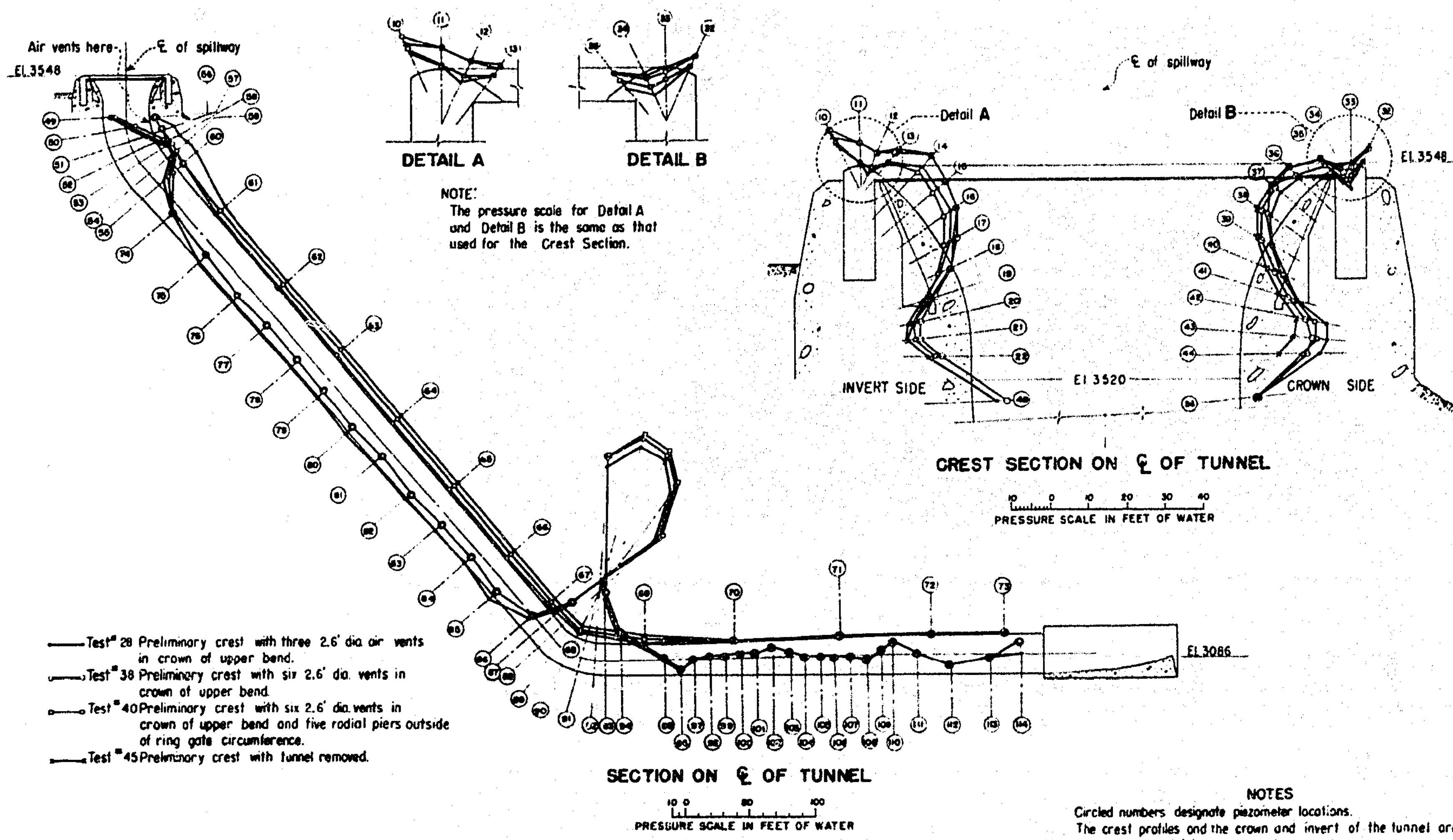
NOTES:
Circled numbers designate piezometer locations. Crest profile is the zero pressure datum. Pressures above atmospheric are plotted toward the center of the morning-glory. Most pressures shown are subatmospheric.

HUNGRY HORSE DAM SPILLWAY
PRESSURE GRADIENTS
PRELIMINARY MORNING-GLORY WITH GATE SEATED
1:36 MODEL

FIGURE 27
REPORT HYD. 355



HUNGRY HORSE DAM SPILLWAY
SPILLWAY PRESSURE GRADIENTS--53,000 SECOND FEET
1:36 MODEL
SHEET 1 OF 2



Test # 28 Preliminary crest with three 2.6' dia air vents in crown of upper bend.

Test # 38 Preliminary crest with six 2.6' dia. vents in crown of upper bend.

Test # 40 Preliminary crest with six 2.6' dia. vents in crown of upper bend and five radial piers outside of ring gate circumference.

Test # 45 Preliminary crest with tunnel removed.

NOTES

Circled numbers designate piezometer locations.

The crest profiles and the crown and invert of the tunnel are zero pressure datums.

Subatmospheric pressures are measured away from the spillway centerline and normal to the pressure datum.

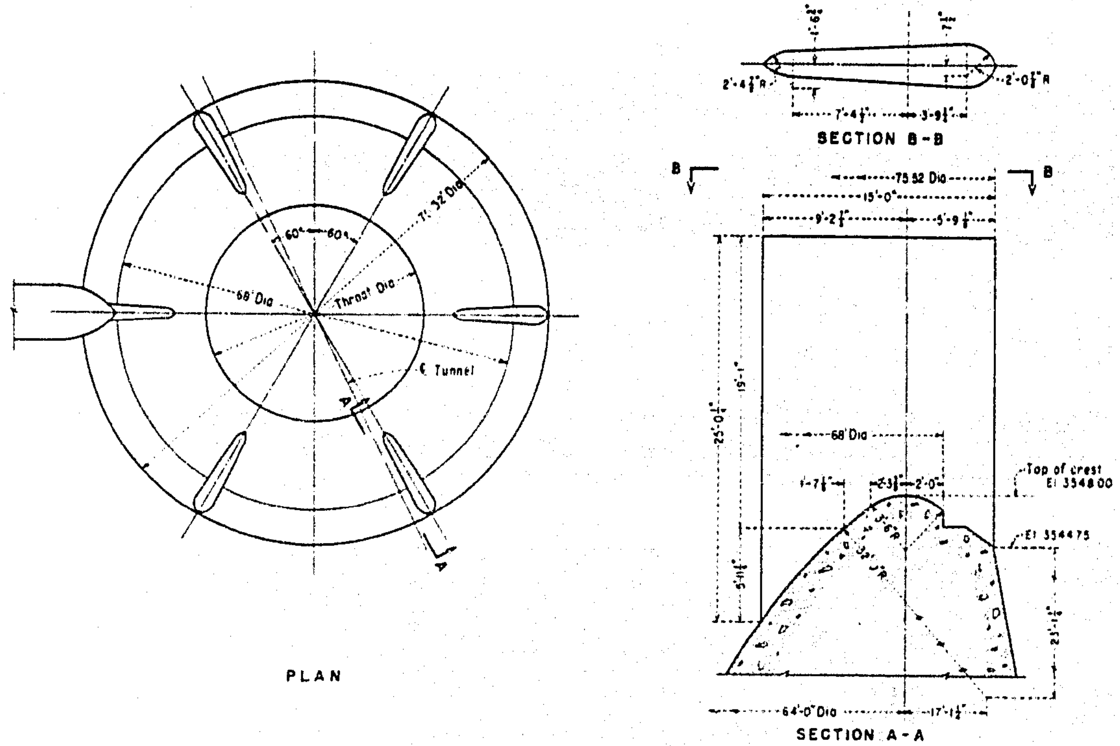
HUNGRY HORSE DAM SPILLWAY

SPILLWAY PRESSURE GRADIENTS--53,000 SECOND FEET

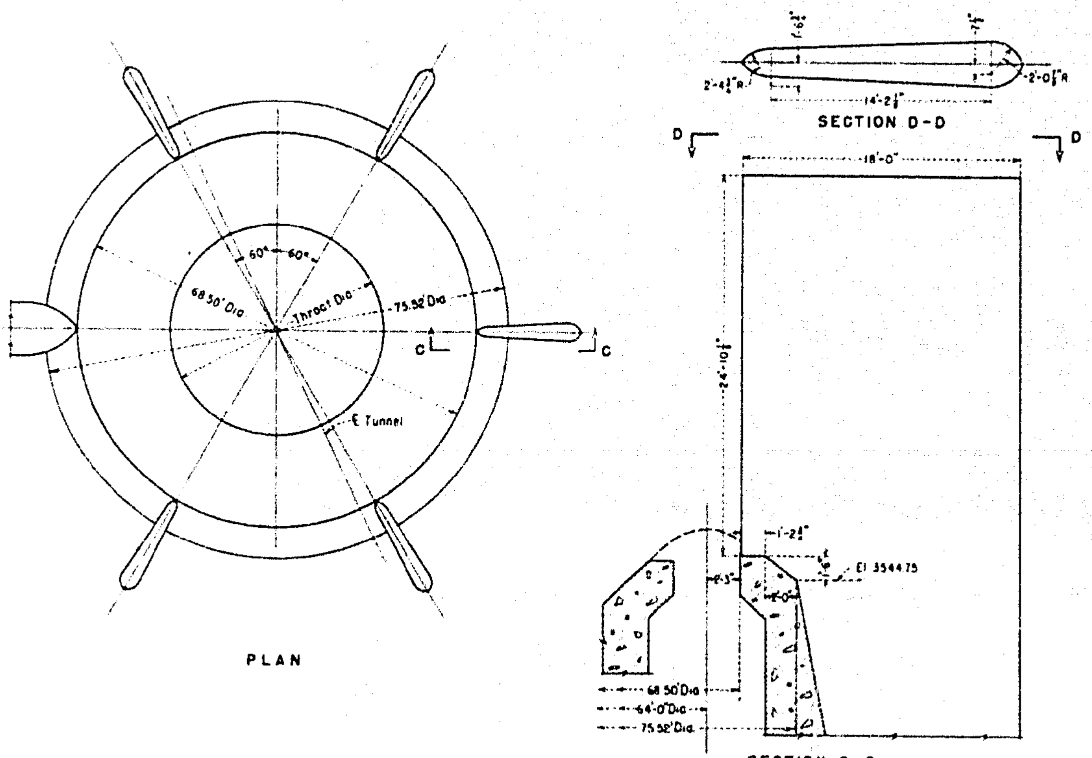
1:36 MODEL

SHEET 2 OF 2

FIGURE 28(b)



(a) SIX RADIAL PIERS ON THE MORNING-GLORY CREST



(b) FIVE RADIAL PIERS OUTSIDE OF RING GATE CIRCUMFERENCE

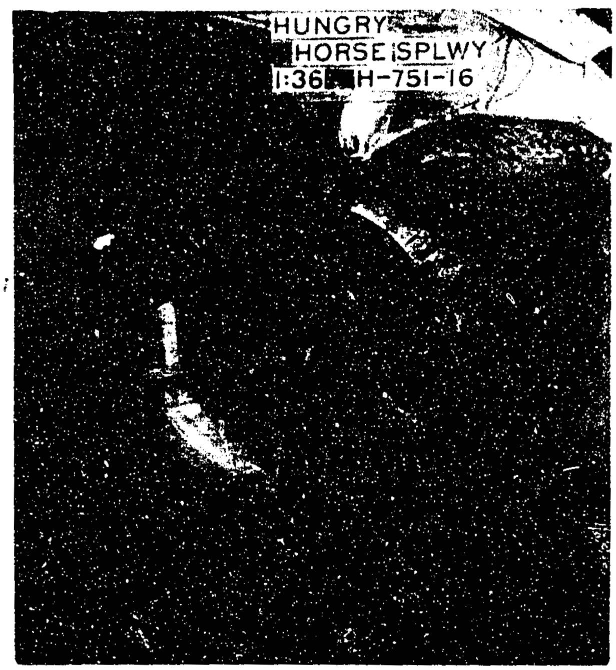
HUNGRY HORSE DAM SPILLWAY

MORNING-GLORY ENTRANCE PIERS

TWO PROPOSED DESIGNS

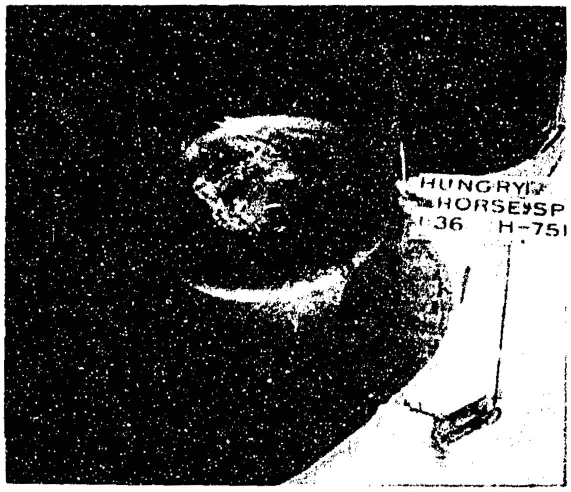
1:36 MODEL

(a) Piers' aid in producing radial flow
Note: Roadway adjacent to control pier is under water.



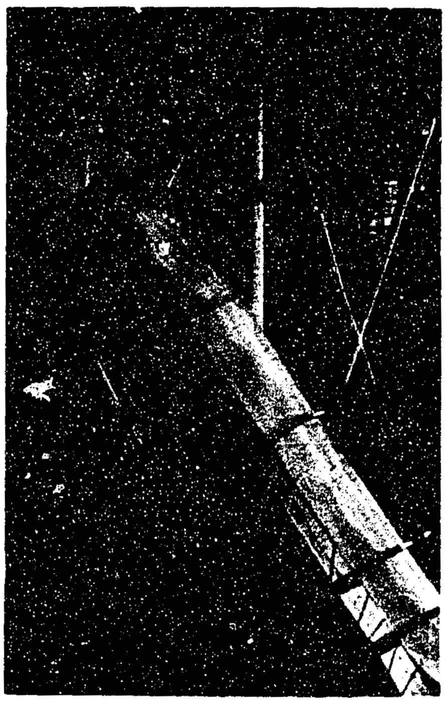
(b) Concentration of flow at control pier is reduced.

HUNGRY HORSE DAM SPILLWAY
Preliminary Morning-Glory with Radial Piers on Crest
53,000 Second-feet
1:36 Model

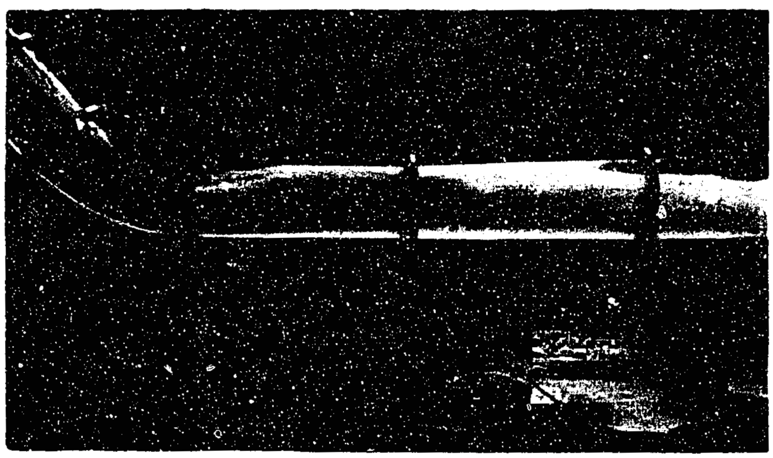


(a) Morning-glory crest.
Note: Submergence is greater than in preliminary design, Figure 21(c).

(b) Upper bend. Note: Air space along the crown of tunnel.

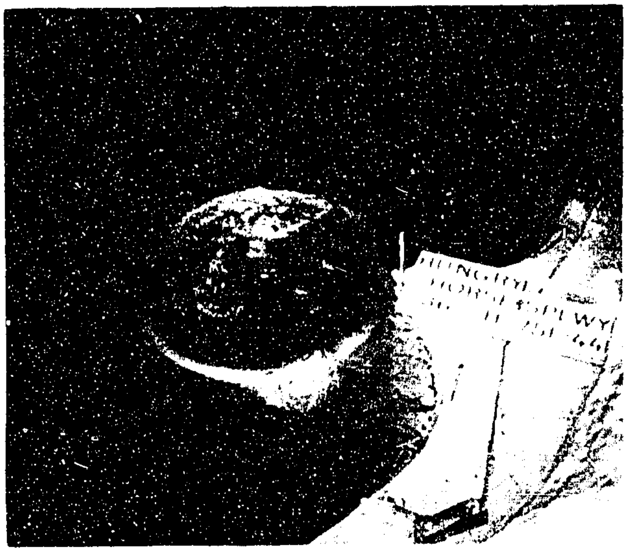


(c) Inclined tunnel. Note: Some surging and zig-zag flow occurs.

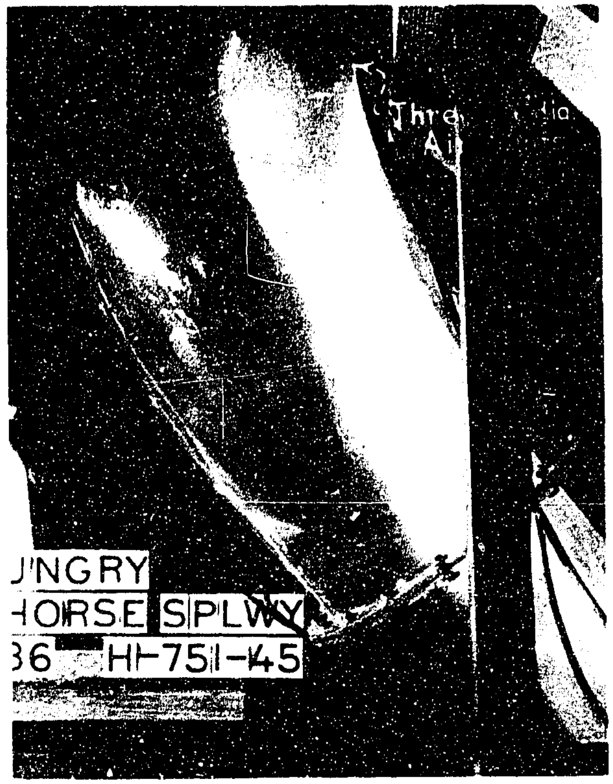


(d) Lower bend and horizontal tunnel. Note: Tunnel is sealed with spray from "dished" flow pattern downstream from lower bend.

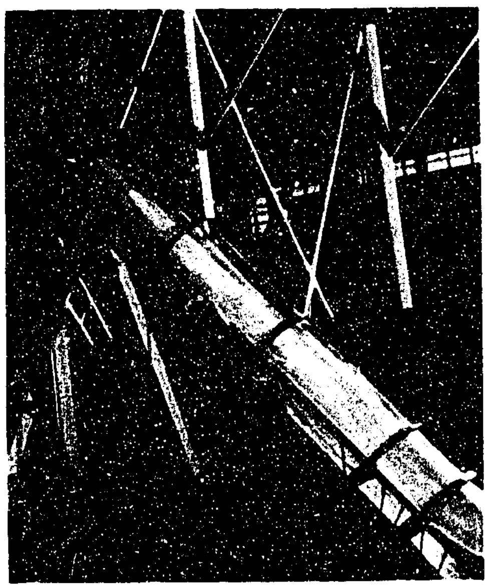
HUNGRY HORSE DAM SPILLWAY
Preliminary Morning-Glory With Three 2.6-Foot Diameter Vents in Crown of Upper Bend--53,000 Second-Feet
1:36 Model



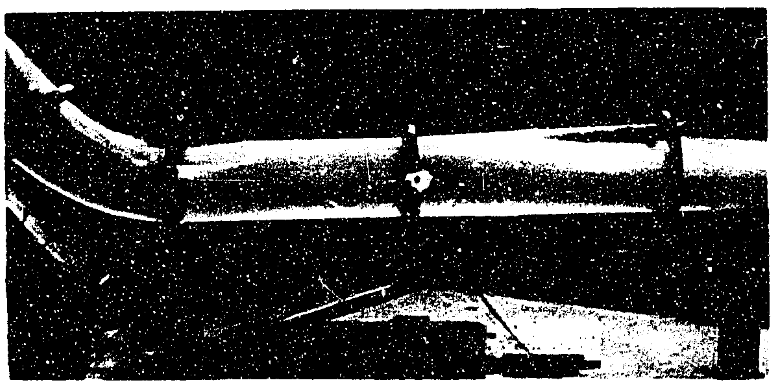
(a) Morning-glory crest. Note: Submergence is greater than in Figure 31(a)



(b) Upper bend. Note: Air space along the crown of tunnel.

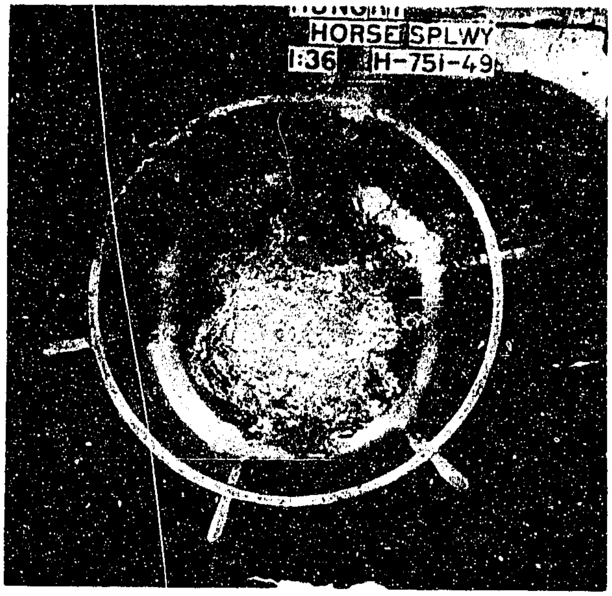


(c) Inclined tunnel. Note: Some zigzag flow but no surging occurs.



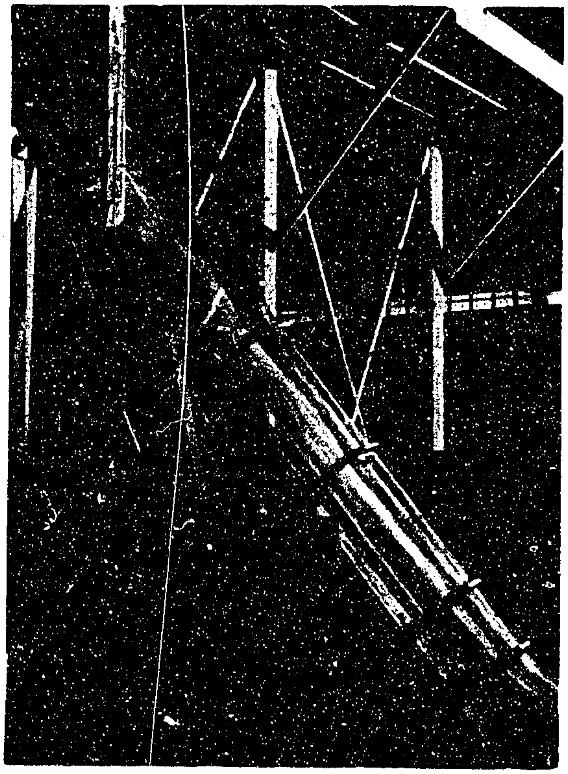
(d) Lower bend and horizontal tunnel. Note: The tunnel is sealed with spray from "dished" flow pattern downstream from lower bend.

HUNGRY HORSE DAM SPILLWAY
Preliminary Morning-Glory with 2.6-foot Diameter Vent
In Crown of Upper Bend--53,000 Second-Feet
1:36 Model

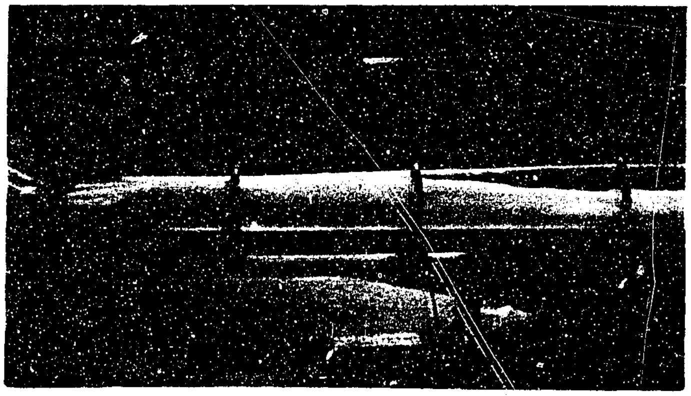


(a) Morning-glory crest. Note: Piers improve flow distribution.

(b) Upper bend. Note: Air space along the crown.

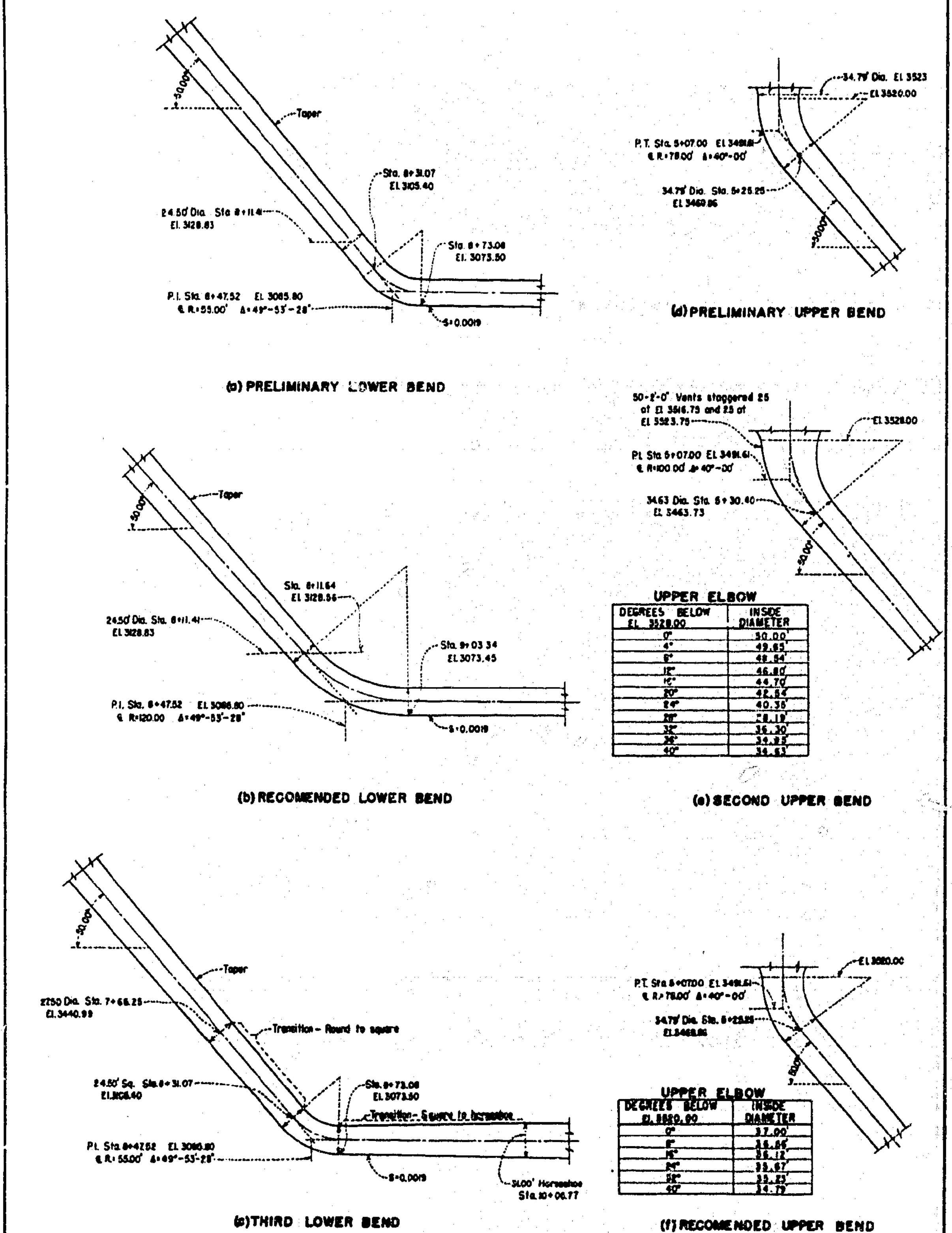


(c) Inclined tunnel. Note: No surge or zigzag flow occurs.



(d) Lower bend and horizontal tunnel. Note: The tunnel is sealed with spray from "dished" flow pattern downstream from lower bend.

HUNGRY HORSE DAM SPILLWAY
Preliminary Morning-Glory With Six 2.6-Foot Diameter Vents
In Upper Bend and Five Radial Piers Outside of Ring Gate
53,000 Second-Feet
1:36 Model



UPPER ELBOW

DEGREES BELOW EL. 3528.00	INSIDE DIAMETER
0°	50.00'
4°	49.65'
8°	48.54'
12°	46.80'
16°	44.70'
20°	42.54'
24°	40.38'
28°	38.19'
32°	36.30'
36°	34.95'
40°	34.63'

UPPER ELBOW

DEGREES BELOW EL. 3520.00	INSIDE DIAMETER
0°	37.00'
8°	36.56'
16°	36.12'
24°	35.67'
32°	35.23'
40°	34.79'

HUNGRY HORSE DAM SPILLWAY

PROPOSED TUNNEL BENDS

1:36 MODEL

(a) 53,000 Second-feet.

(b) 35,000 Second-feet--Ring gate seated.

Preliminary Lower Bend--55-foot Radius

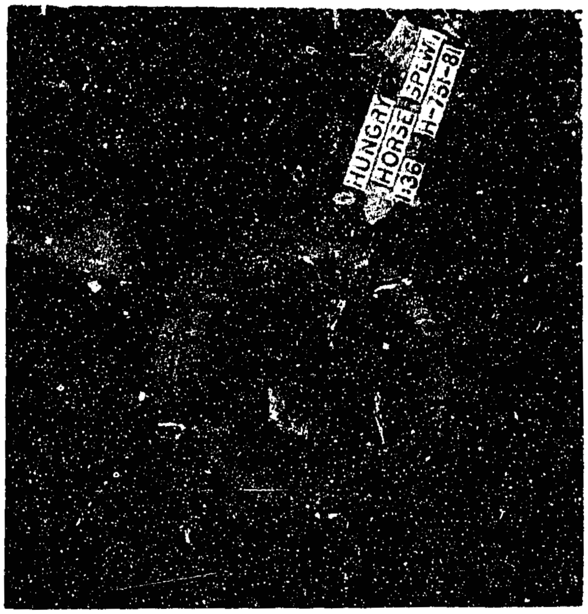
(c) 53,000 Second-feet

(d) 35,000 Second-feet. Ring gate seated.

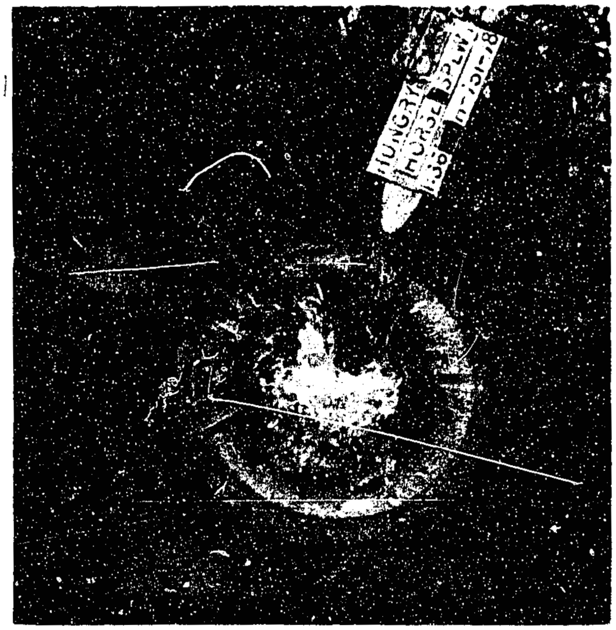
Recommended Lower Bend--120-foot Radius

Note: The preliminary crest with radial piers outside of ring gate and six 2.6-foot diameter vents in upper bend were used with these studies.

HUNGRY HORSE DAM SPILLWAY
Comparison of Preliminary and Recommended Lower Bends
1:36 Model

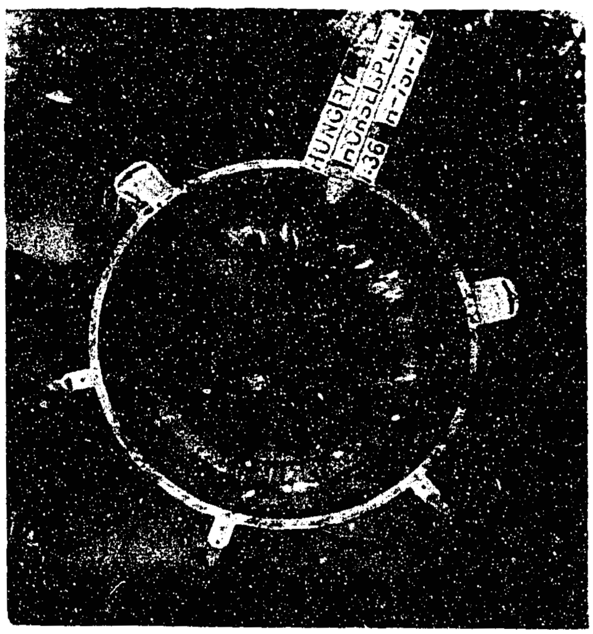


(a) Undernappe failed to vent.



(b) Undernappe was vented by external means.

Note: Upper Bend and Inclined Tunnel was not used in Figures (a), (b) and (c).



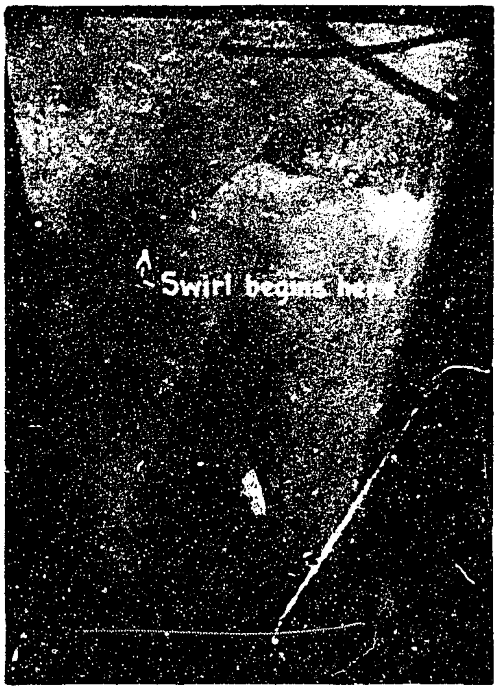
(c) Radial piers failed to vent the undernappe.

(d) Square nose control pier vents the undernappe.

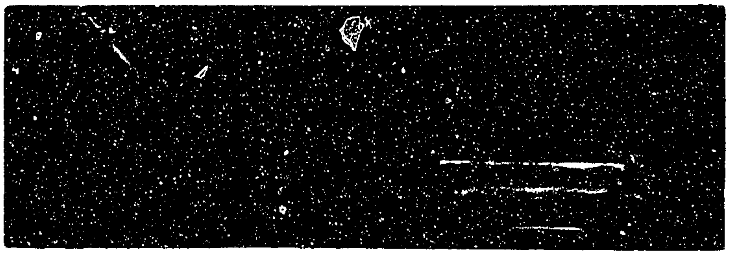
HUNGRY HORSE DAM SPILLWAY
Flow Entering Model Arrangements of the Second Morning-Glory
Gate Seated--53, 000 Second-Feet
1:36 Model

(a) Second crest with square nose control pier--Gate seated and undernappe ventilated.

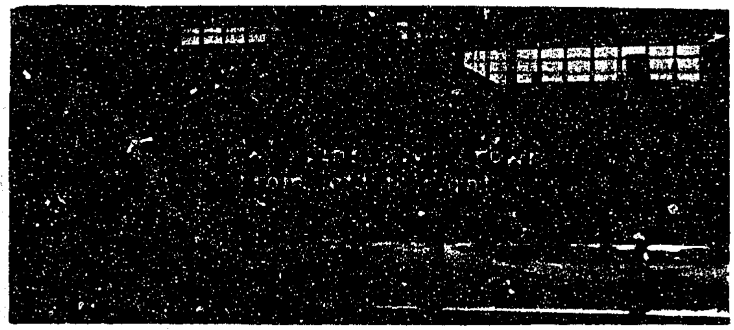
(b) Upper bend--Gate seated and undernappe ventilated.



(c) Invert of upper bend--Gate seated and undernappe ventilated.

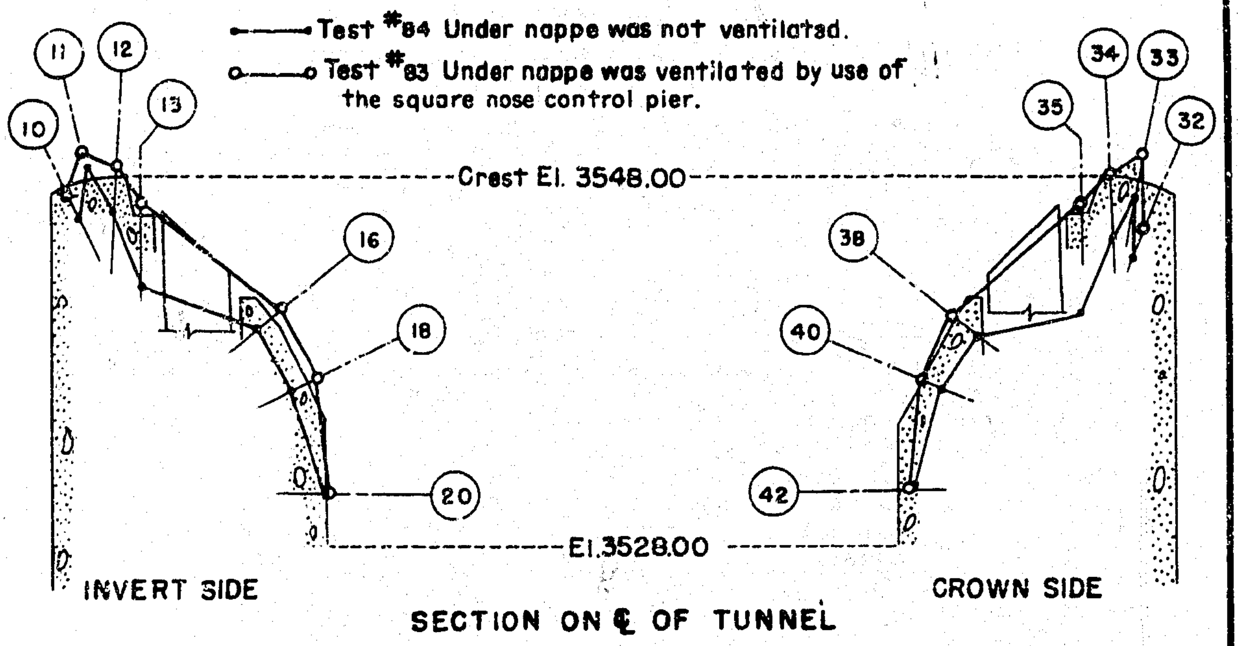


(d) Recommended lower bend--Gate seated and undernappe ventilated--Flow zigzags.

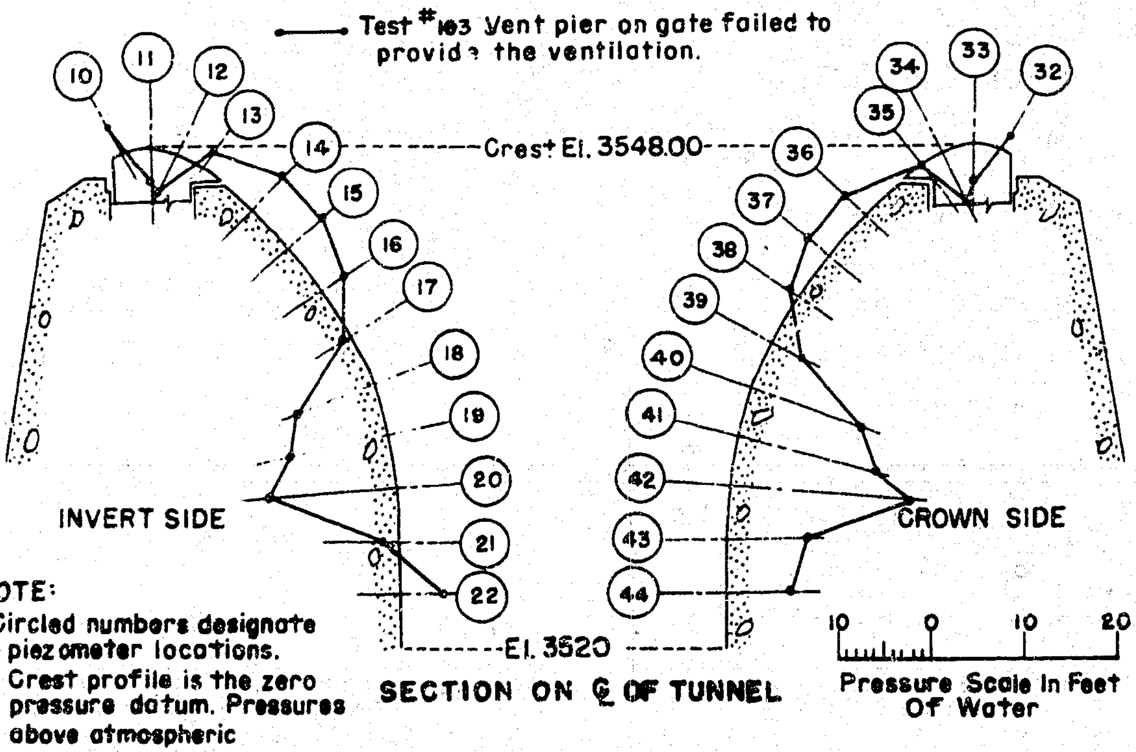


(e) Recommended lower bend--Gate elevated to El. 3549 and the undernappe ventilated--Zigzag flow prominant.

HUNGRY HORSE DAM SPILLWAY
Second Morning-Glory with Square Nose Control Pier
35,000 Second-Feet
1:36 Model



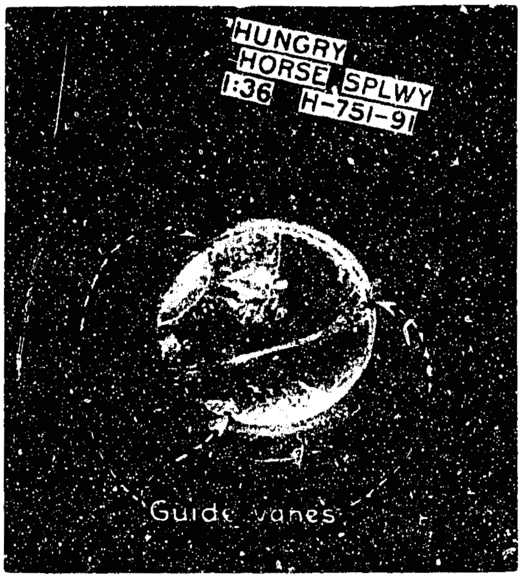
(a) SECOND CREST WITH NO TUNNEL BELOW THROAT EL. 3528



NOTE:
Circled numbers designate piezometer locations.
Crest profile is the zero pressure datum. Pressures above atmospheric are plotted toward the center of the morning-glory.

(b) THIRD CREST WITH VENT PIER ON GATE AND 80 SQ. FT. VENT IN UPPER BEND

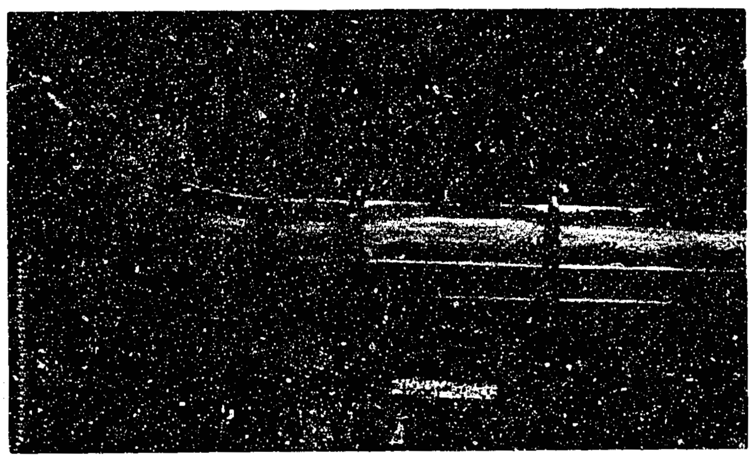
HUNGRY HORSE DAM SPILLWAY
PRESSURE GRADIENTS -- SECOND AND THIRD MORNING-GLORYS --
53,000 SECOND FEET
1:36 MODEL



(a) Crest--Gate seated--
1000 second-feet.

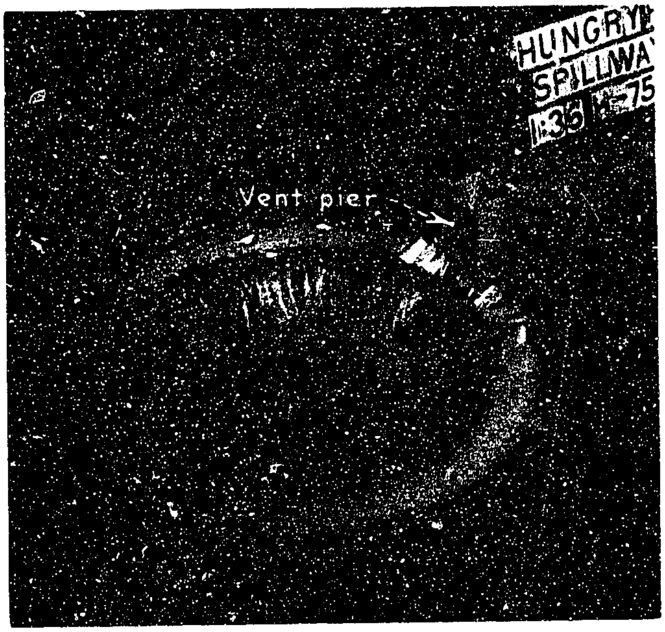
(b) Upper bend--35,000 second-feet--
Gate seated and undernappe ventilated.

(c) Invert of upper bend--
35,000 second-feet--
Gate seated and under-
nappe ventilated.

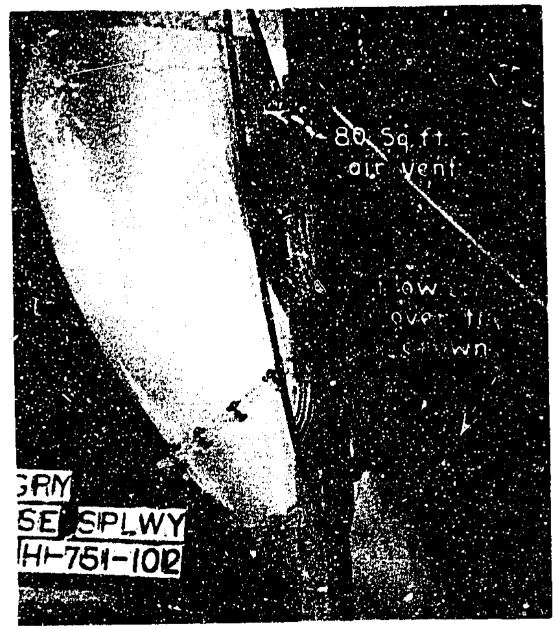


(d) Recommended lower bend--35,000
second-feet--Gate seated and under-
nappe ventilated--Flow does not zig-
zag.

HUNGRY HORSE DAM SPILLWAY
Second Morning-Glory in Operation with Square Nose Control Pier
and Three Guide Vanes in Upper Bend
1:36 Model

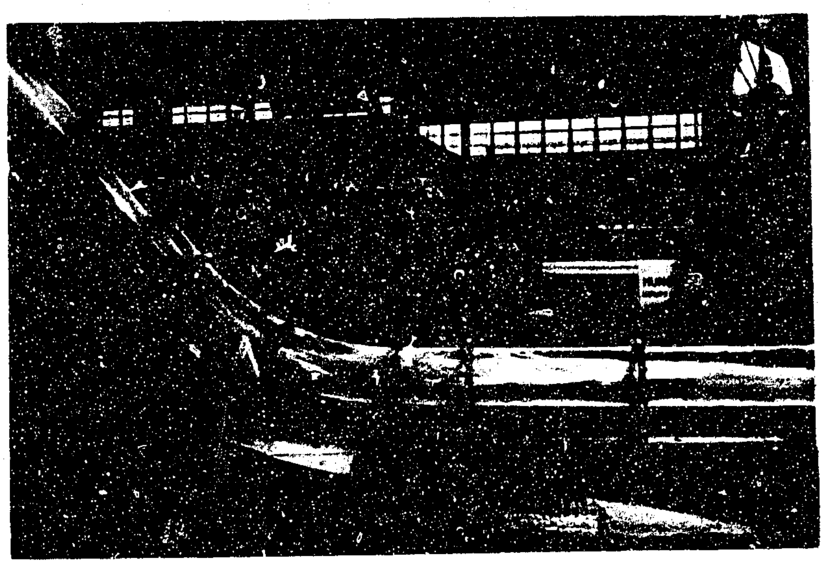


(a) Crest--15,000 Second-feet-
Gate elevated.



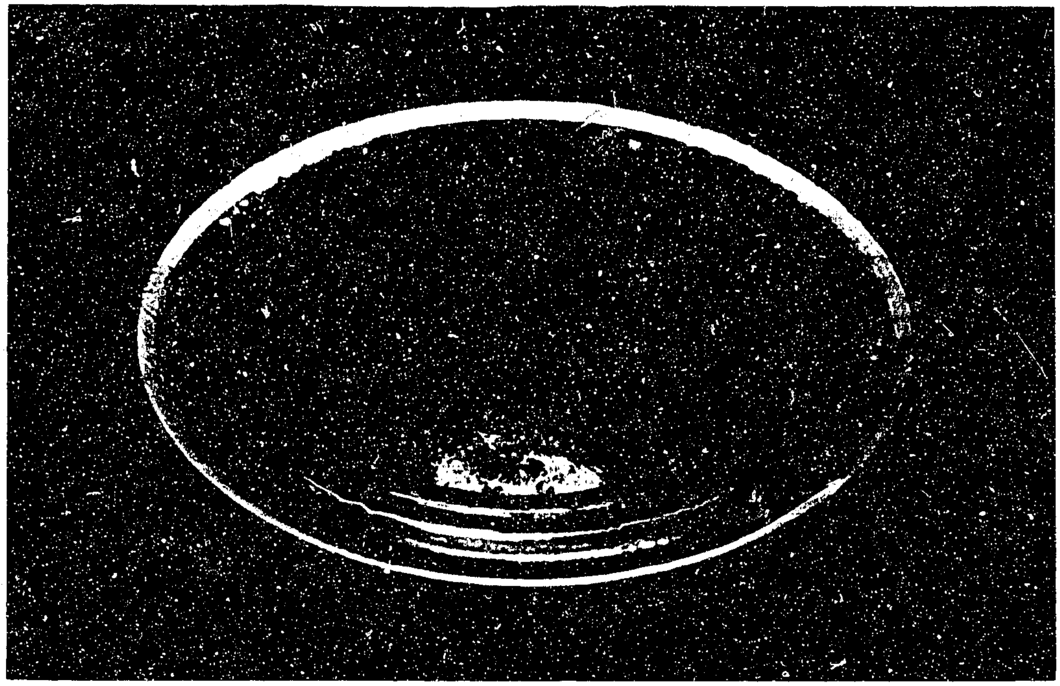
(b) Upper bend--35,000 second-
feet--Gate elevated.

(c) Invert of Upper bend--35,000
second-feet--Gate elevated.

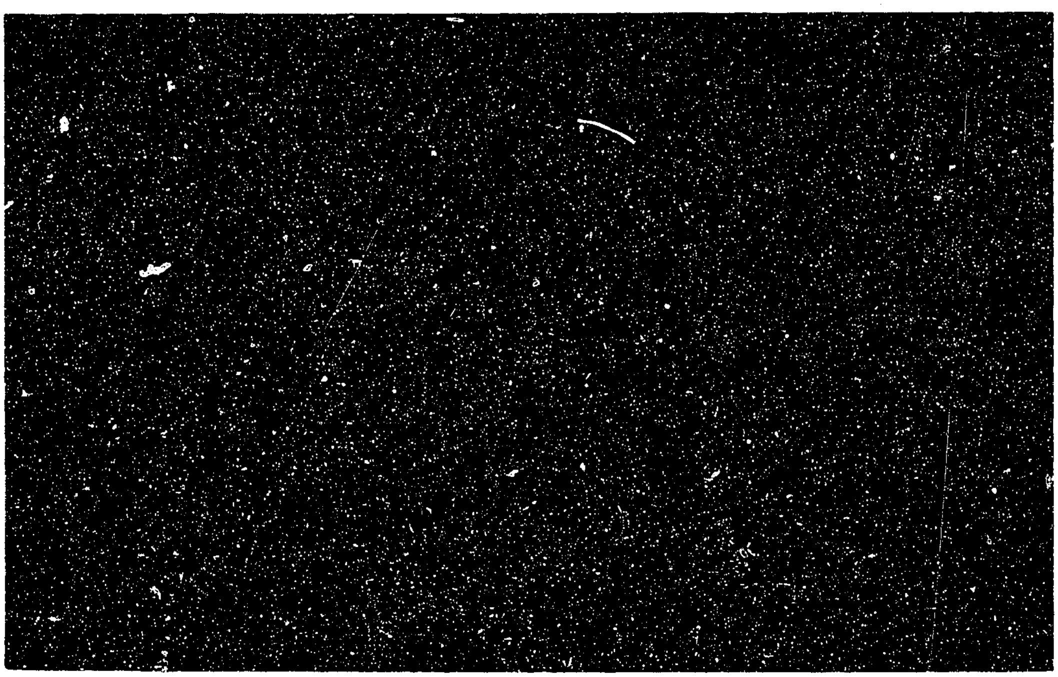


(d) Recommended lower bend--35,000
second-feet--Gate elevated.

HUNGRY HORSE DAM SPILLWAY
Third Morning-Glory in Operation with Vent Pier on Gate and
80 Square Foot Vent in Upper Bend
1:36 Model

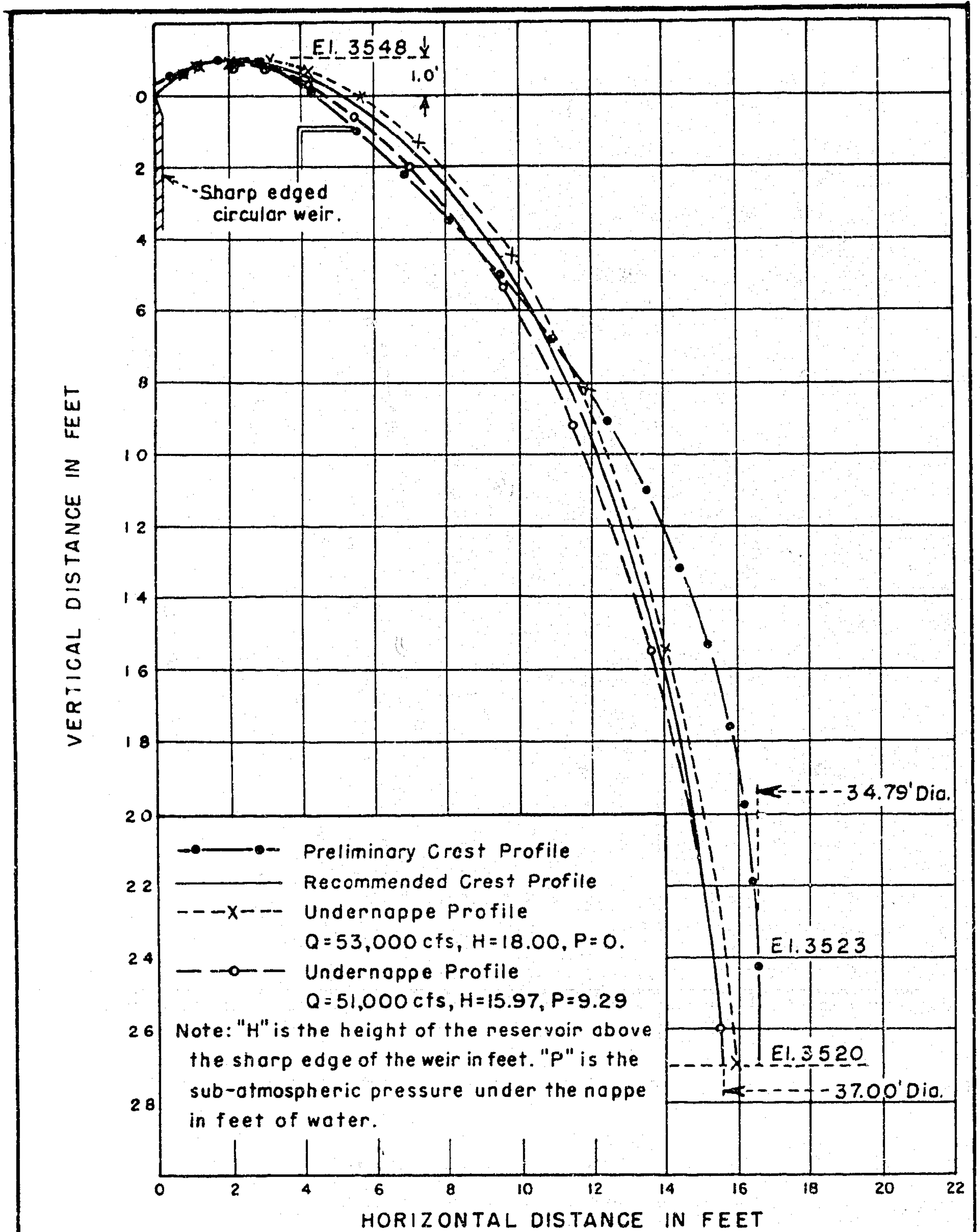


Crest not submerged.

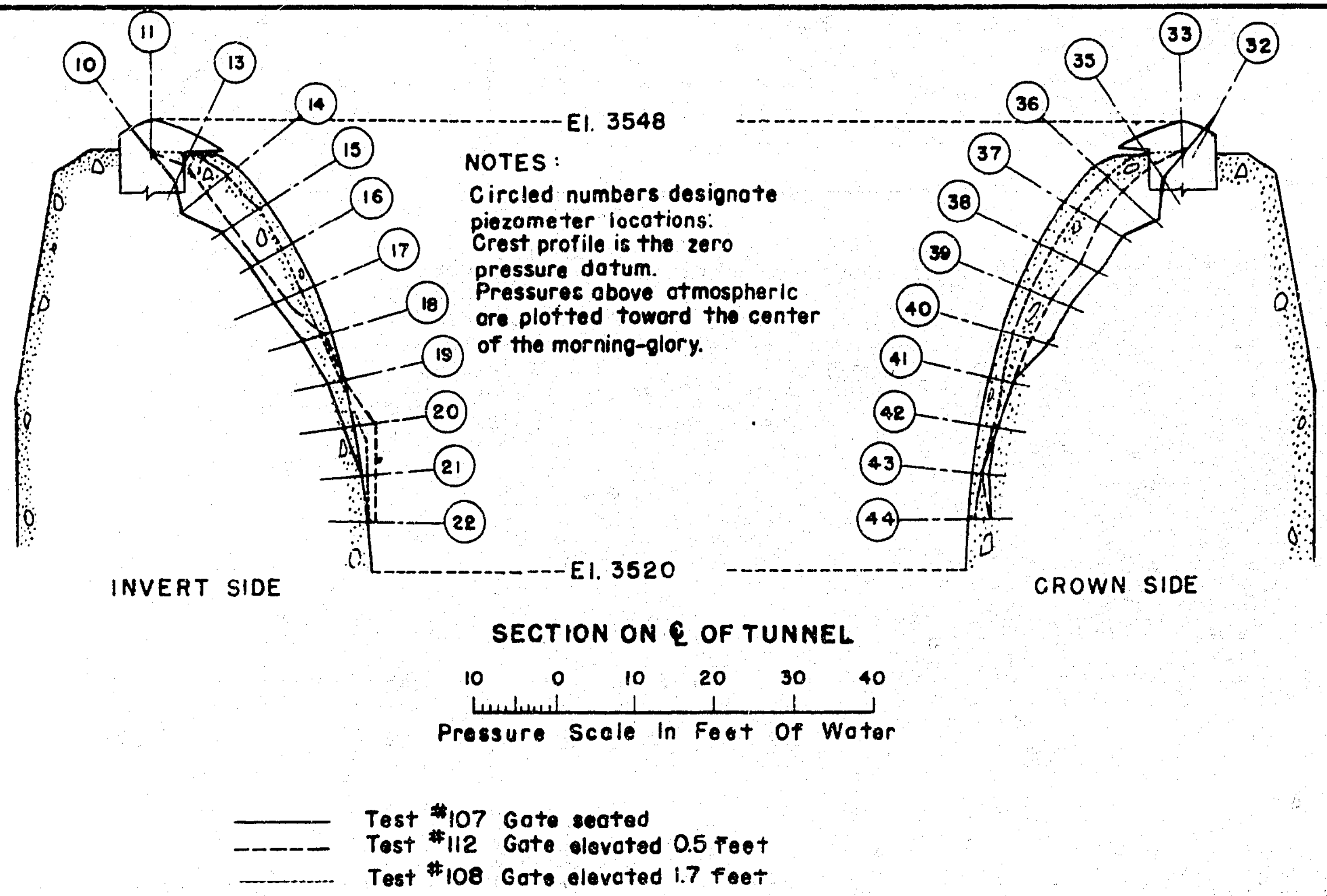


Crest submerged.

HUNGRY HORSE DAM SPILLWAY
Circular Weir Discharging
1:40.94 Circular Weir Model



HUNGRY HORSE DAM SPILLWAY
CIRCULAR WEIR UNDERNAPPE PROFILES
1:40.94 CIRCULAR WIER MODEL



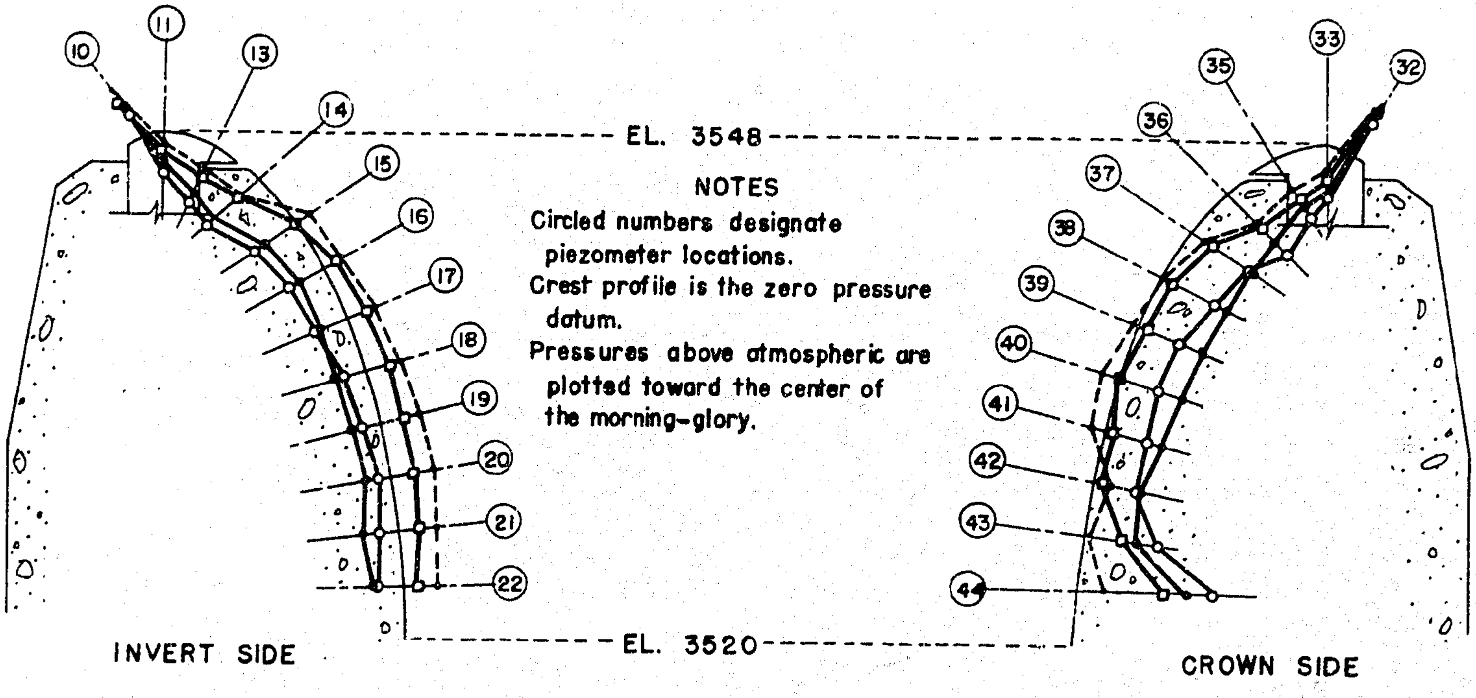
HUNGRY HORSE DAM SPILLWAY

PRESSURE GRADIENTS -- RECOMMENDED MORNING-GLORY WITH PROPOSED VENT PIER ON GATE AND AN 80 SQUARE FOOT VENT IN CROWN OF UPPER BEND -- 45,000 SECOND FEET

1:36 MODEL

FIGURE 43
REPORT HYD. 355

FIGURE 44(a)
REPORT HYD. 355



CREST SECTION ON ℄ OF TUNNEL

10 0 10 20 30 40

Pressure scale in feet of water

- - - - - Test # 107 - Pier vent on gate and 80 sq. ft. of vent area in crown of upper bend.

□——□ Test # 118 - 80 sq. ft. of vent area in crown of upper bend with no other vents.

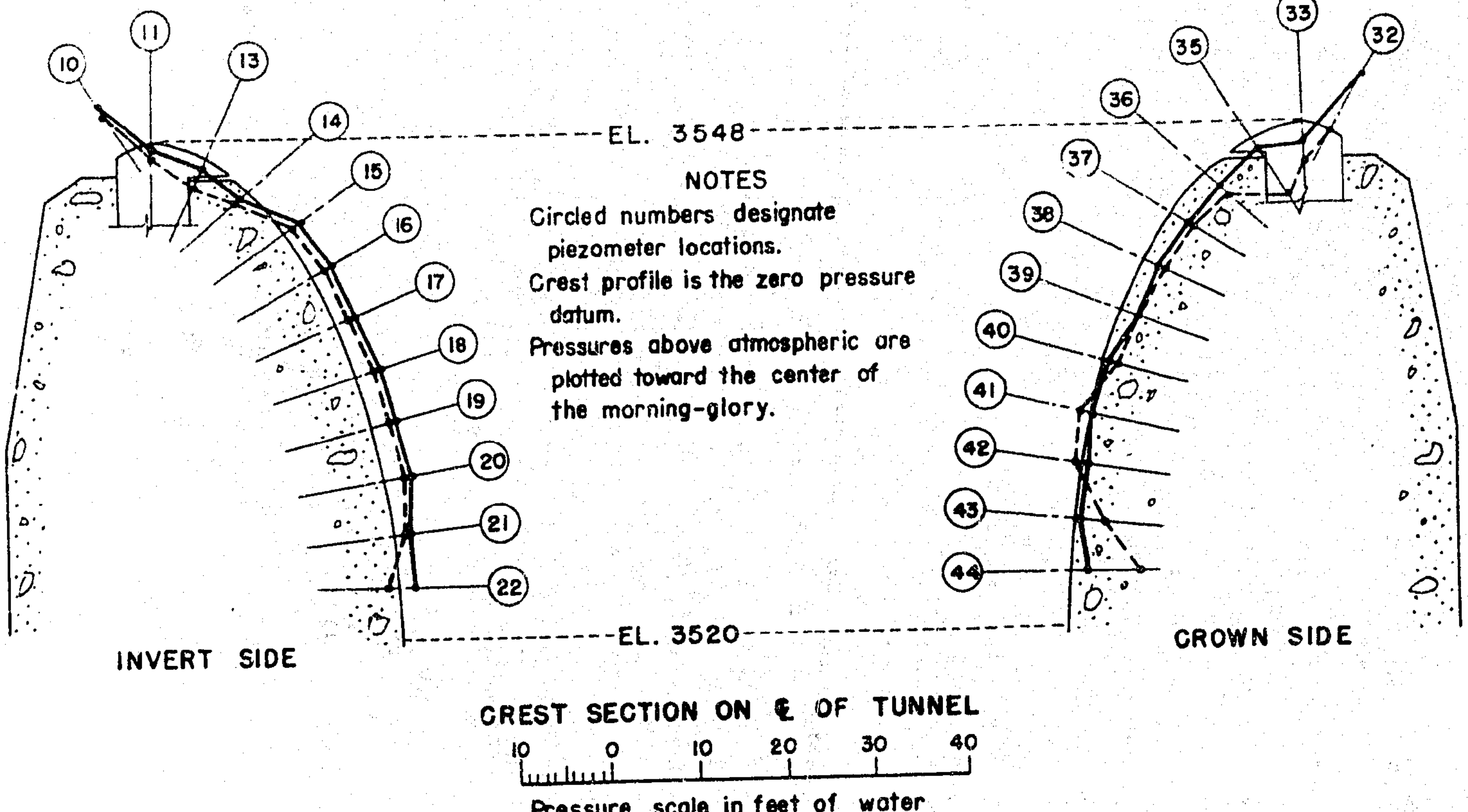
○——○ Test # 119 - No vent anywhere in structure.

●——● Test # 120 - Eight vents of one sq. ft. each under gate lip but no vent in crown of upper bend.

HUNGRY HORSE DAM SPILLWAY

PRESSURE GRADIENTS - - RECOMMENDED MORNING-GLORY WITH SEVERAL PROPOSED VENTING SYSTEMS - - 50,000 SECOND FEET

1:36 MODEL



——— Test #121- Eight vents of one sq. ft. each under gate lip and 80 sq. ft. of vent area in crown of upper bend.

- - - - - Test #140- Recommended venting system- 9 vents under gate lip and 36 sq. ft. of vent area in crown of upper bend.

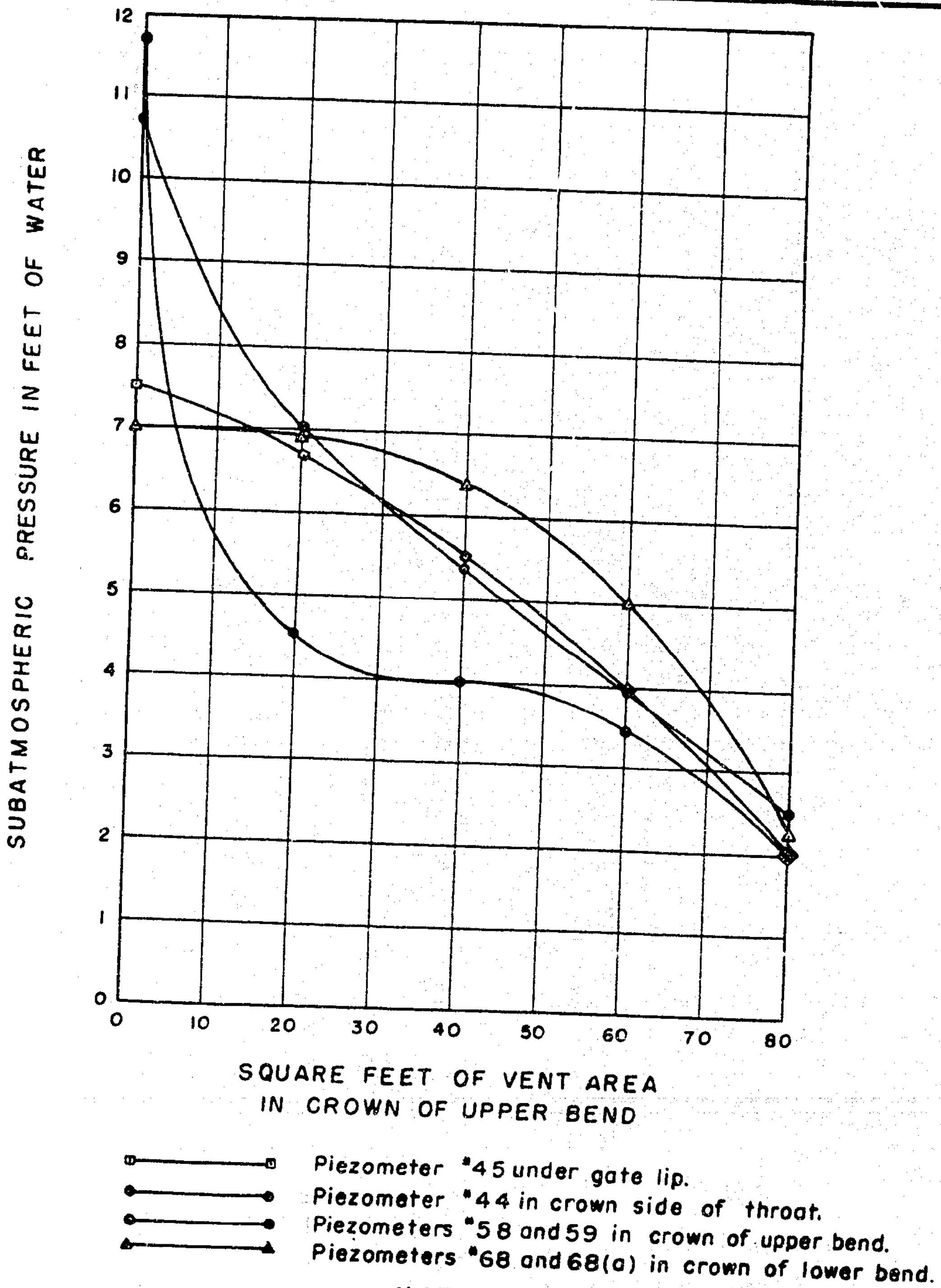
HUNGRY HORSE DAM SPILLWAY

PRESSURE GRADIENTS -- RECOMMENDED MORNING-GLORY WITH SEVERAL PROPOSED VENTING SYSTEMS -- 50000 SECOND FEET

1:36 MODEL

SHEET 2 OF 2

FIGURE 44(b)
REPORT HYD.355



NOTE
The under nappe was vented by use of 8 individual vents located under the gate lip.

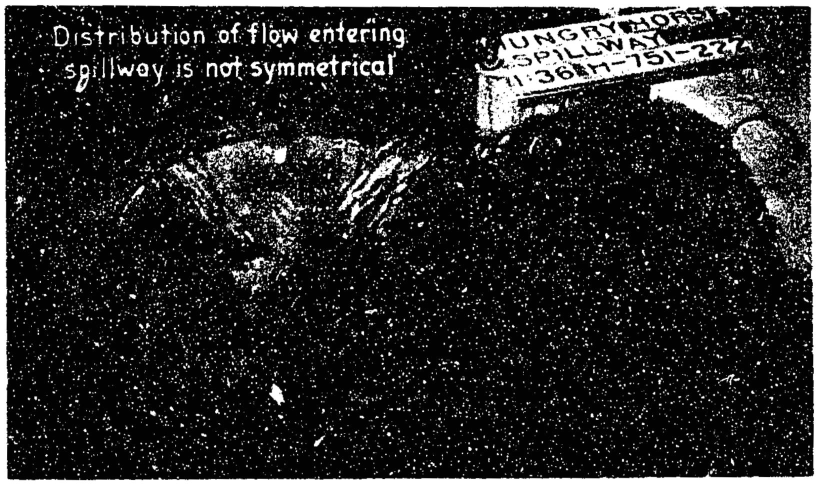
HUNGRY HORSE DAM SPILLWAY

VENT AREA IN CROWN OF UPPER BEND VS. PRESSURE IN SUB-ATMOSPHERIC PRESSURE REGIONS OF THE SPILLWAY

1:36 MODEL

(a) Reservoir dry--Gate seated.

(b) Res. El 3560- Gate elevated--15,000 second-feet.

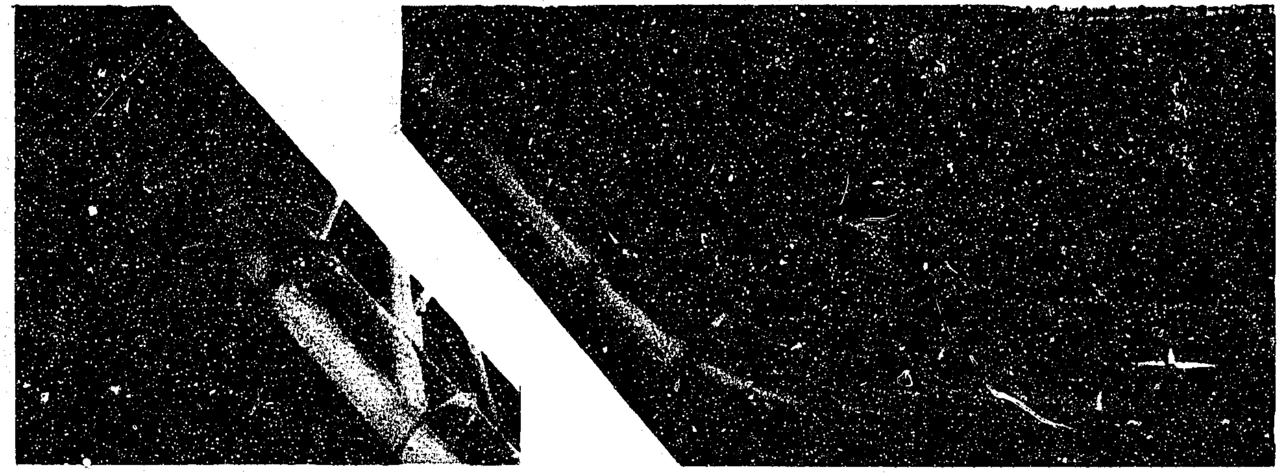


(c) Res. El 3561--Gate seated--35,000 second-feet.

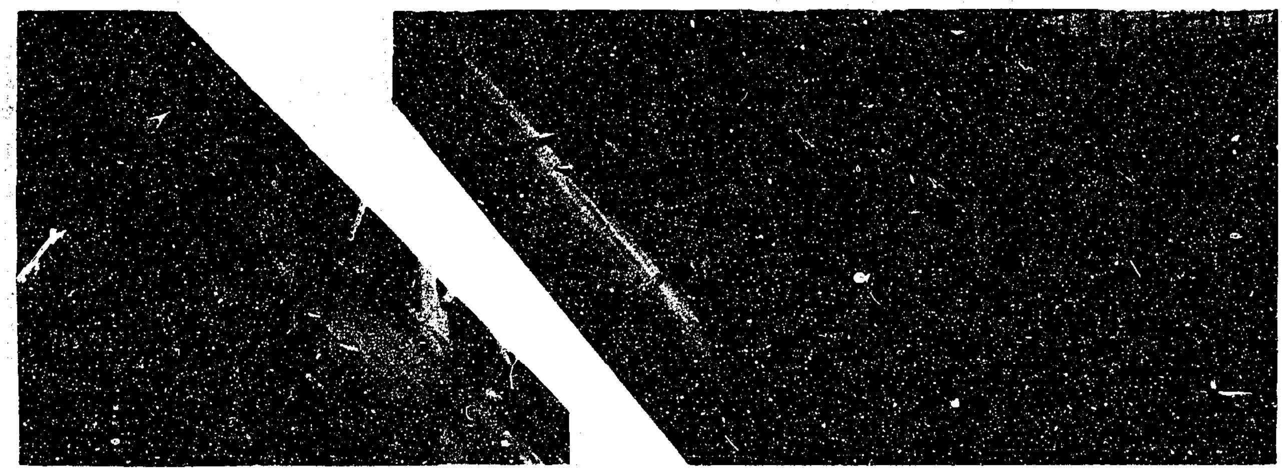
(d) Res. El 3565--Gate seated--50,000 second-feet.

HUNGRY HORSE DAM SPILLWAY
Flow Entering Recommended Morning-Glory with the Recommended
Venting System and Tunnel
1:36 Model

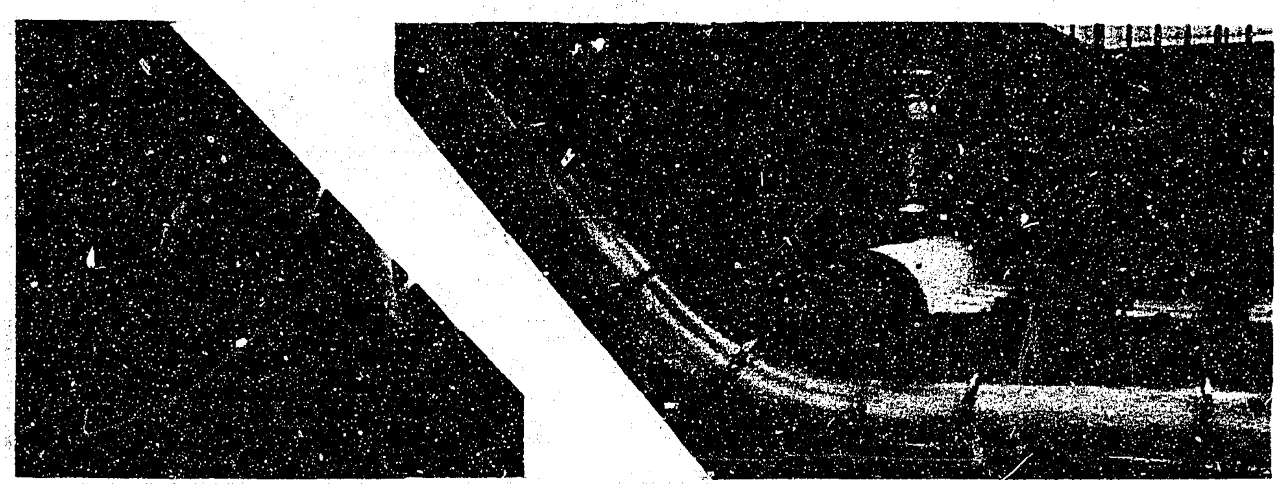
Figure 46
Report Hyd 355



(a) Res. El 3560--Gate elevated--15,000 second-feet.



(b) Res. El 3561--Gate seated--35,000 second-feet.

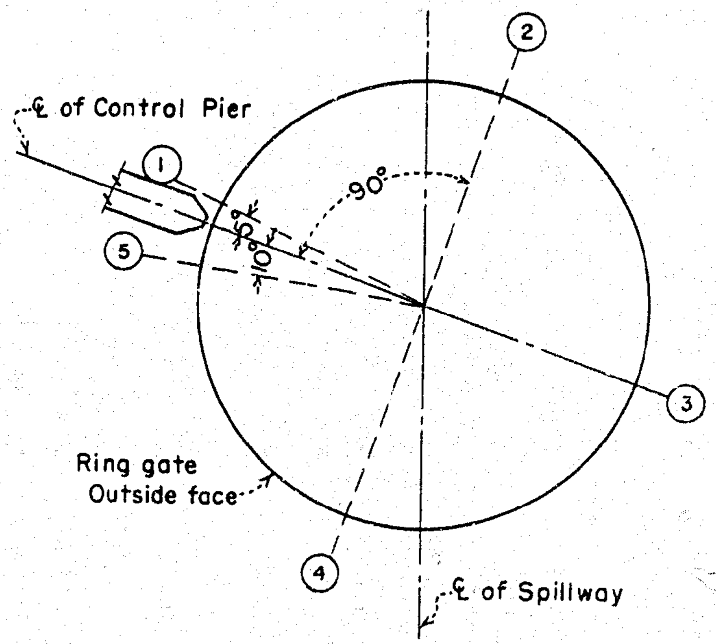


(c) Res. El 3565--Gate seated--50,000 second-feet.
Note: Flow is fairly straight.

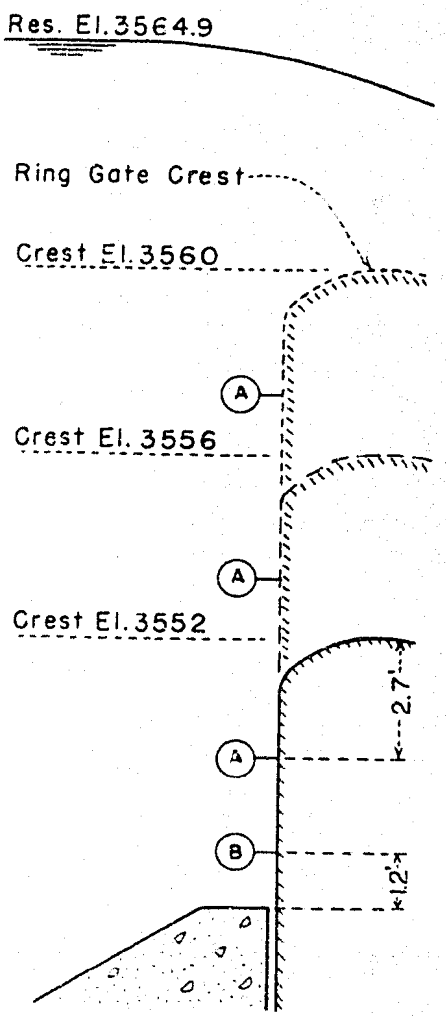
HUNGRY HORSE DAM SPILLWAY
Flow Through the Tunnel--Recommended Morning-Glory, Venting System and Tunnel
1:36 Model

NOTES

Circled numbers designate points where pressures were measured.
Circled letters designate piezometer locations.



LOCATION DIAGRAM
PLAN VIEW



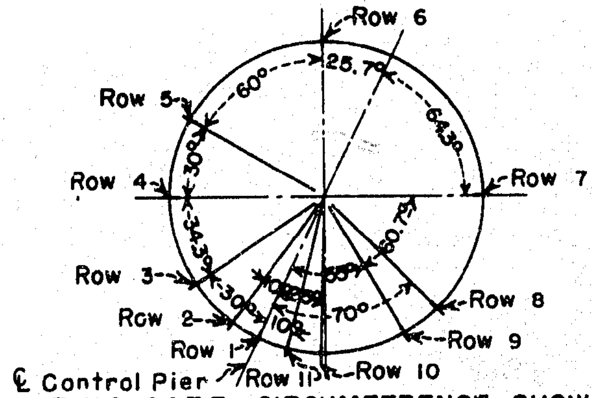
PIEZOMETER LOCATIONS
AT A PRESSURE
MEASURING POINT

PIEZOMETOR LOCATION	RING GATE CREST ELEV. (FT.)	PRESSURE MEASUREMENT * IN FT. OF WATER ABOVE ATOMOSPHERIC AT POINTS 1 TO 5				
		1	2	3	4	5
A	3552	13.9 TO 15.2	14.2	14.4	14.2 TO 14.5	13.4 TO 15.4
B	3552	16.0 TO 17.5	15.9	16.1	16.2 TO 16.7	16.7 TO 17.2
A	3556	11.0	11.0	10.9	10.9	11.0 TO 11.4
B	3556	17.6	17.6	17.5	17.5	17.7
A	3560	7.3	7.4	7.4	7.4	7.4
B	3560	17.7	17.6	17.7	17.6	17.7

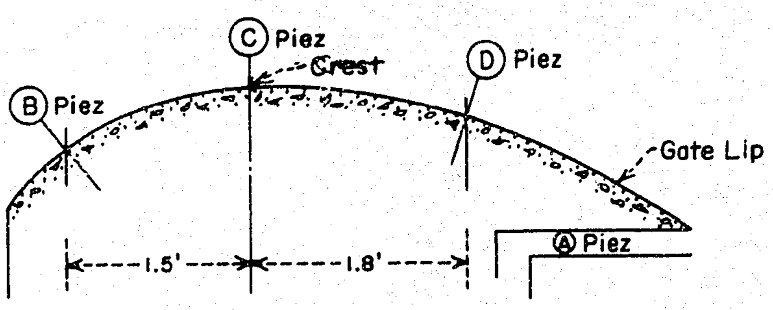
* Pressure measurement were made with Res. W.S. at El. 3564.9

HUNGRY HORSE DAM SPILLWAY
PRESSURE ON SIDE OF RING GATE
RECOMMENDED MORNING-GLORY, RING GATE, AND VENTING SYSTEM
1:36 MODEL

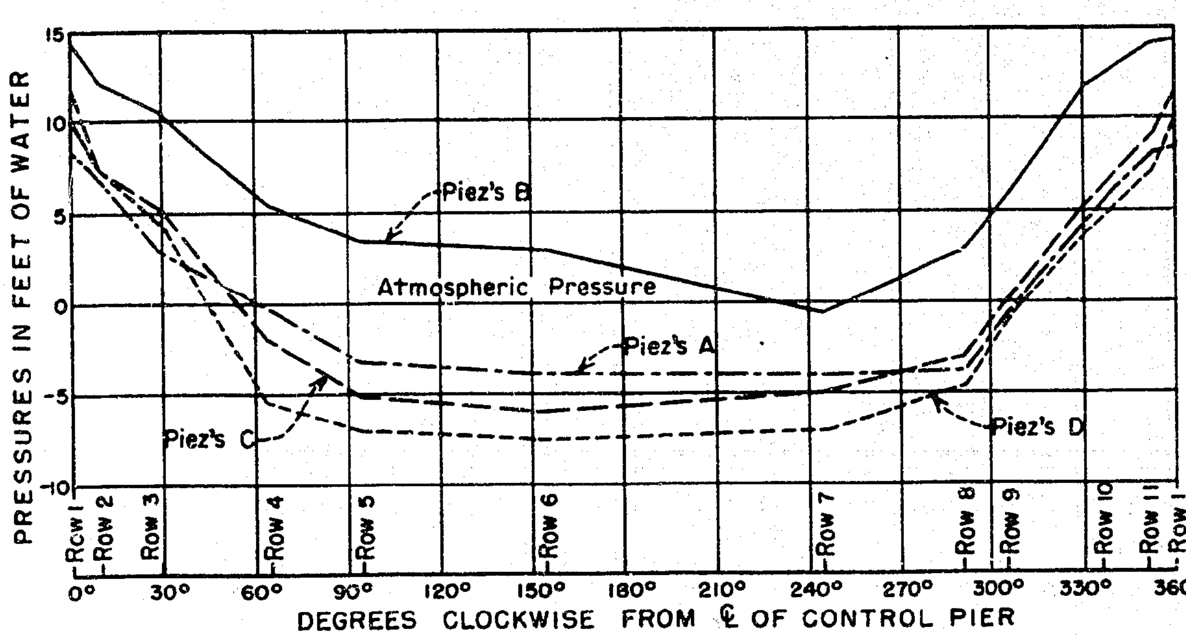
Data from test #161



RING GATE CIRCUMFERENCE SHOWING LOCATION OF PIEZOMETER ROWS



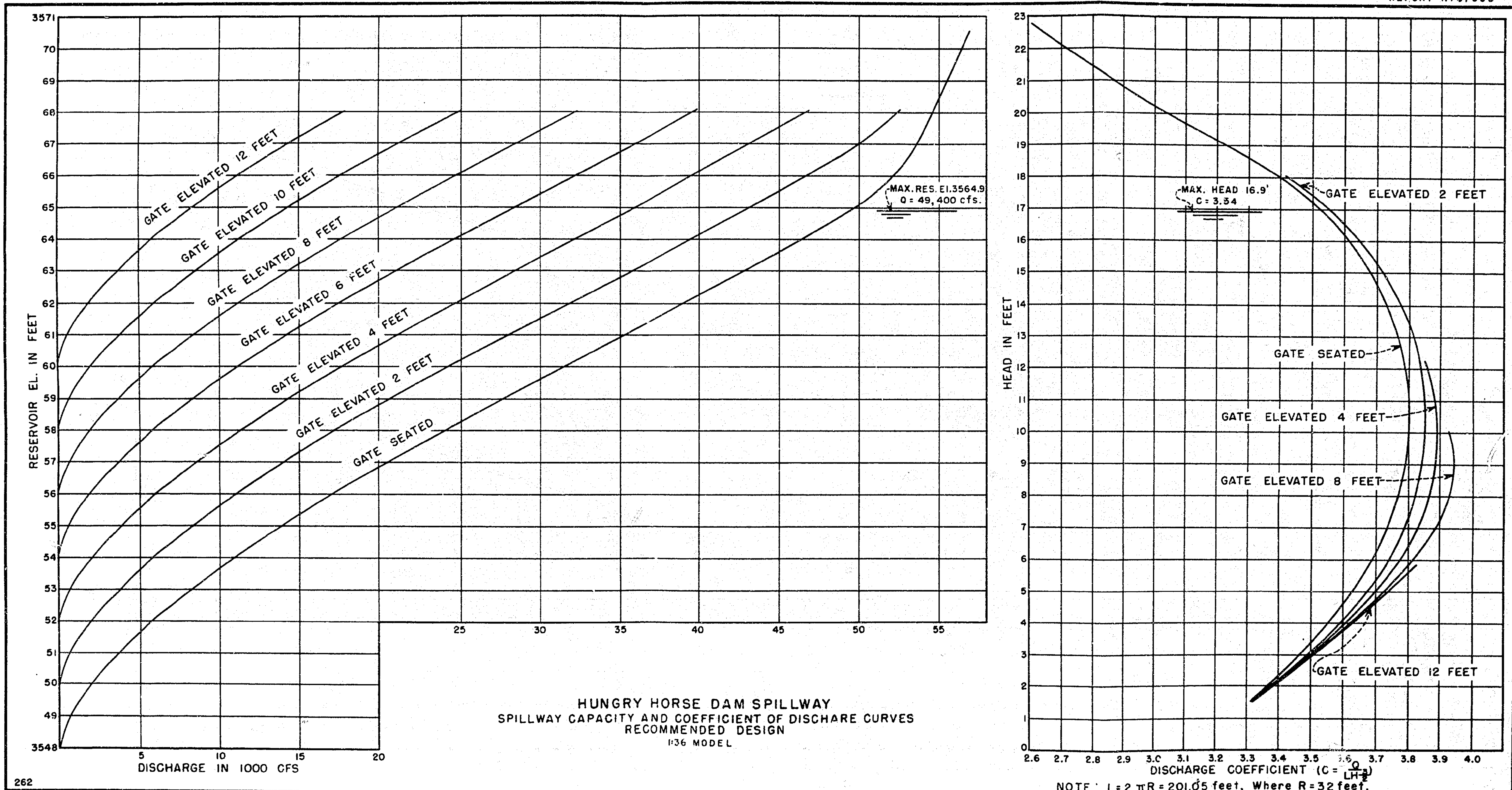
TYPICAL GATE CREST SECTION SHOWING PIEZOMETER LOCATION PER ROW



HUNGRY HORSE DAM SPILLWAY

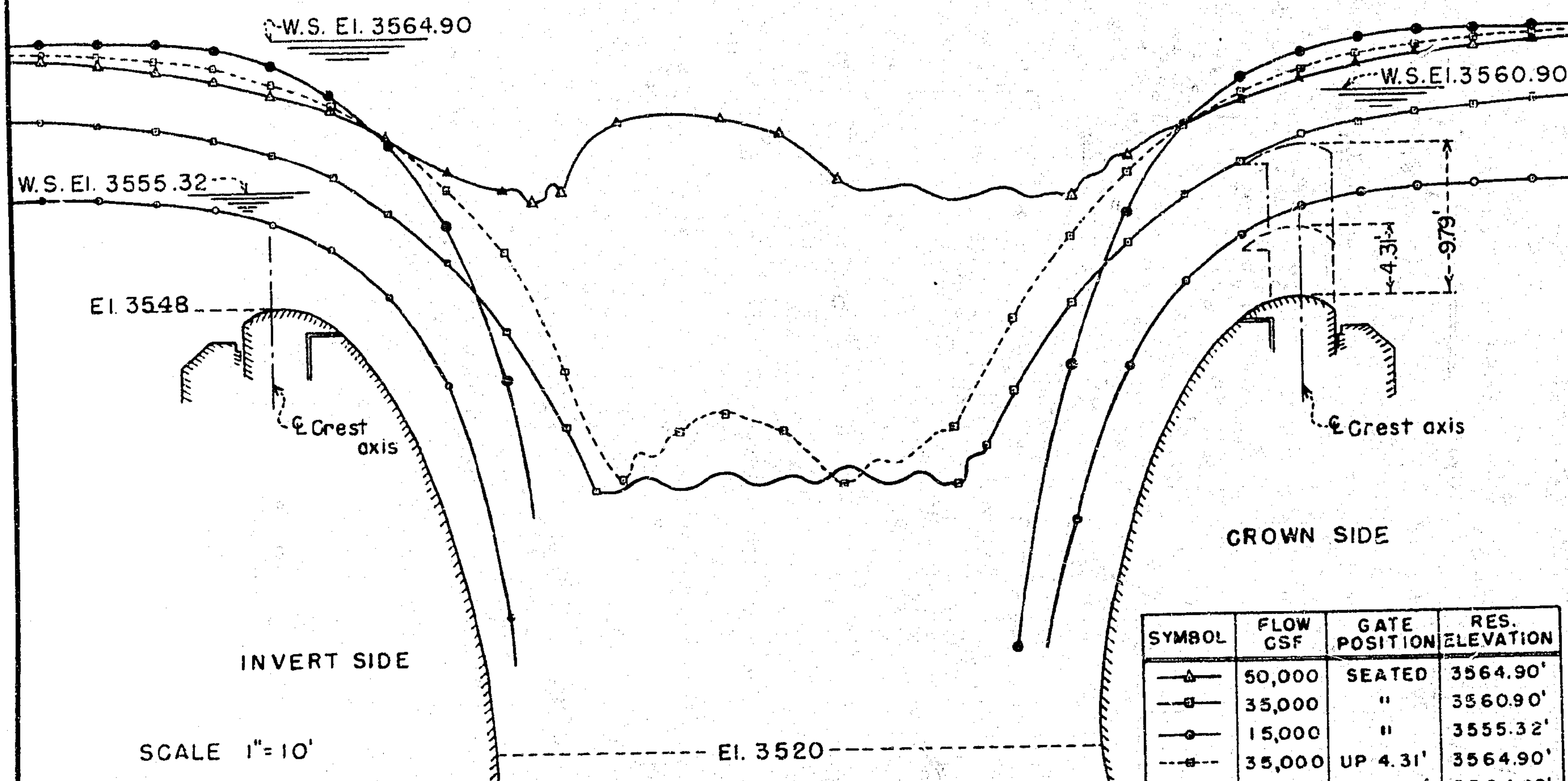
PRESSURE GRADIENTS ON RING GATE AND UNDER LIP--
RECOMMENDED MORNING-GLORY, RING GATE AND VENTING SYSTEM--
50,000 SECOND FEET

1:36 MODEL



HUNGRY HORSE DAM SPILLWAY
SPILLWAY CAPACITY AND COEFFICIENT OF DISCHARE CURVES
RECOMMENDED DESIGN
1:36 MODEL

NOTE: $L = 2\pi R = 201.05$ feet, Where $R = 32$ feet.

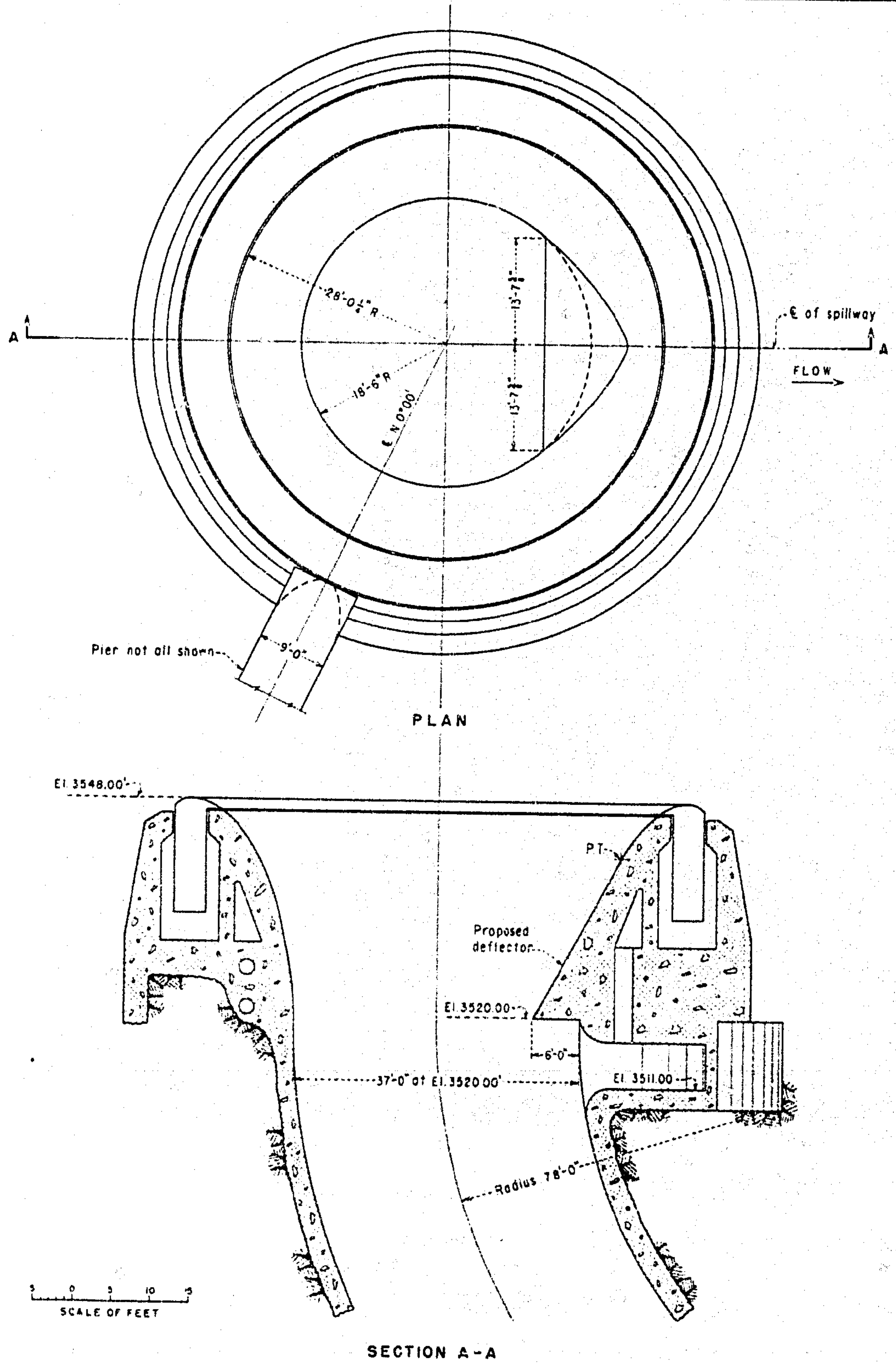


SYMBOL	FLOW CSF	GATE POSITION	RES. ELEVATION
	50,000	SEATED	3564.90'
	35,000	"	3560.90'
	15,000	"	3555.32'
	35,000	UP 4.31'	3564.90'
	15,000	UP 9.79'	3564.90'

SECTION ON ℄ OF TUNNEL
HUNGRY HORSE DAM SPILLWAY
MORNING-GLORY WATER SURFACE PROFILES
RECOMMENDED DESIGN
1:36 MODEL

FIGURE 52
REPORT HYD. 355

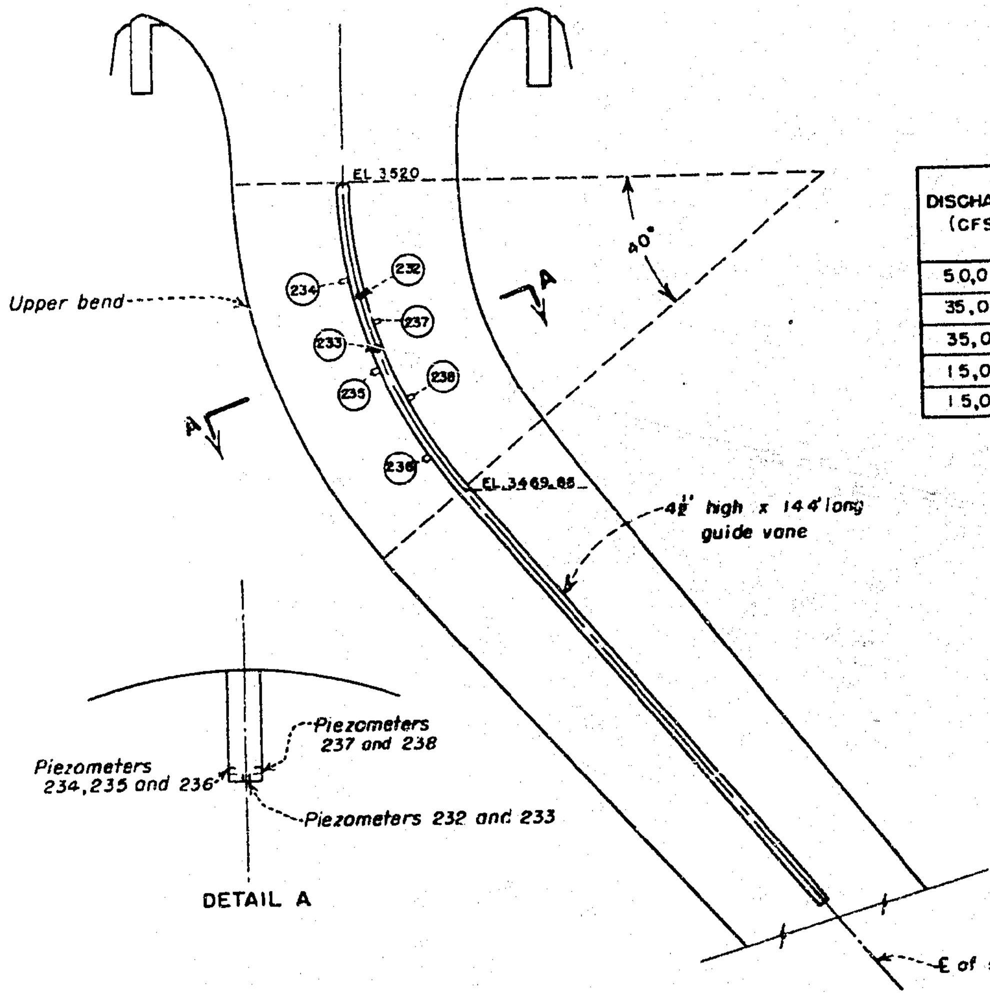
FIGURE 53
REPORT HYD. 355



HUNGRY HORSE DAM SPILLWAY

PROPOSED DEFLECTOR FOR THE MORNING-GLORY

1:36 MODEL

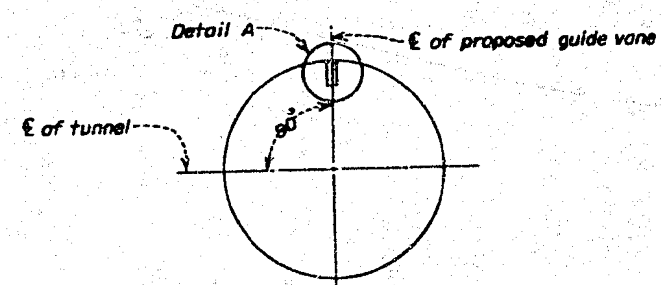


SECTION ON CENTER LINE OF TUNNEL

DISCHARGE (CFS)	GATE POSITION	RES. EL. (FT)	PIEZOMETER PRESSURES* (FEET OF WATER)						
			232	233	234	235	236	237	238
50,000	Seated	3564.9	5.6	10.8	7.6	10.4	14.4	14.1	22.7
35,000	Seated	3560.9	2.8	4.5	2.8	9.3	10.4	4.4	15.5
35,000	Elevated	3564.9	-1.5	4.5	2.2	14.8	12.6	0.5	14.8
15,000	Seated	3555.3	-5.2	-5.4	-0.7	-3.6	-4.0	-1.0	0
15,000	Elevated	3564.9	-3.7	-11.5	-2.9	-3.1	-2.9	-7.6	14.4

* Atmospheric pressure is zero pressure.

Note: Circled numbers designate piezometer locations.

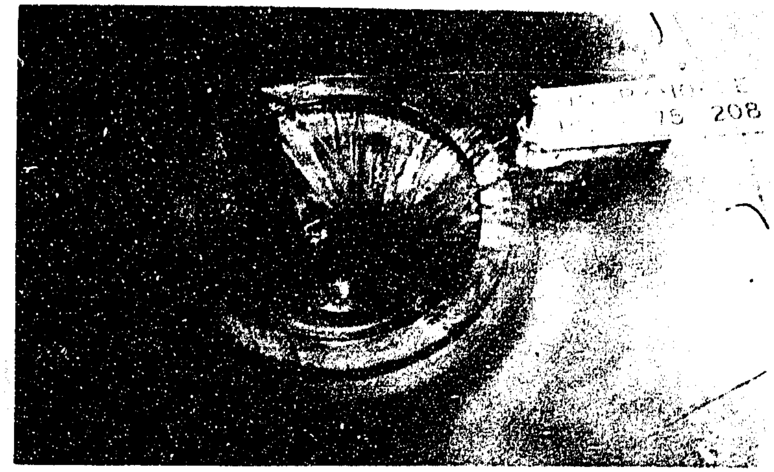


SECTION A-A

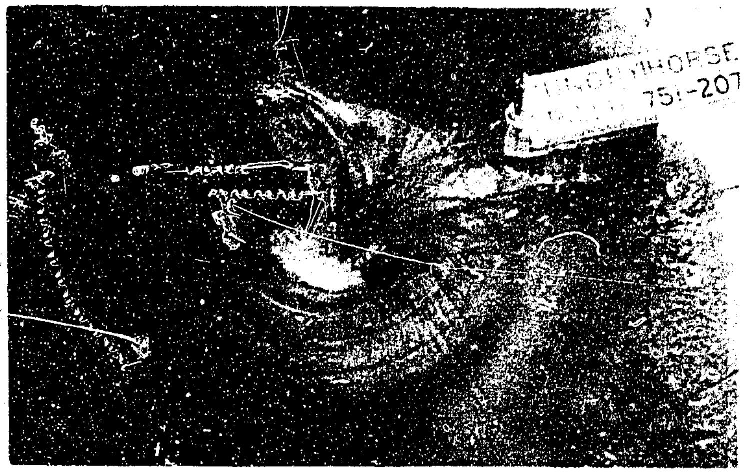
HUNGRY HORSE DAM SPILLWAY
PRESSURES ON THE PROPOSED GUIDE VANE
1:36 MODEL

FIGURE 54
REPORT HYD 355

(a) Reservoir dry--Gate seated



Res. El 3560--Gate elevated--15,000 second-feet.

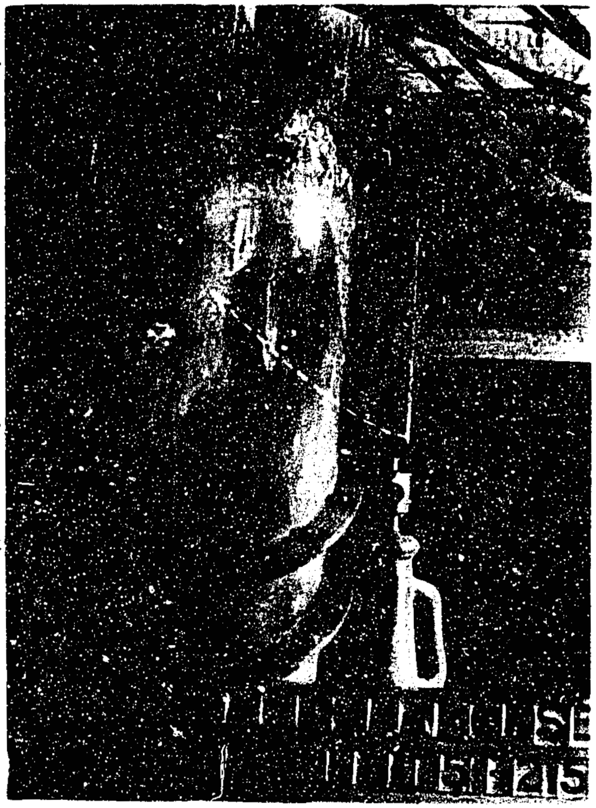


(c) Gate seated--35,000 second-feet.

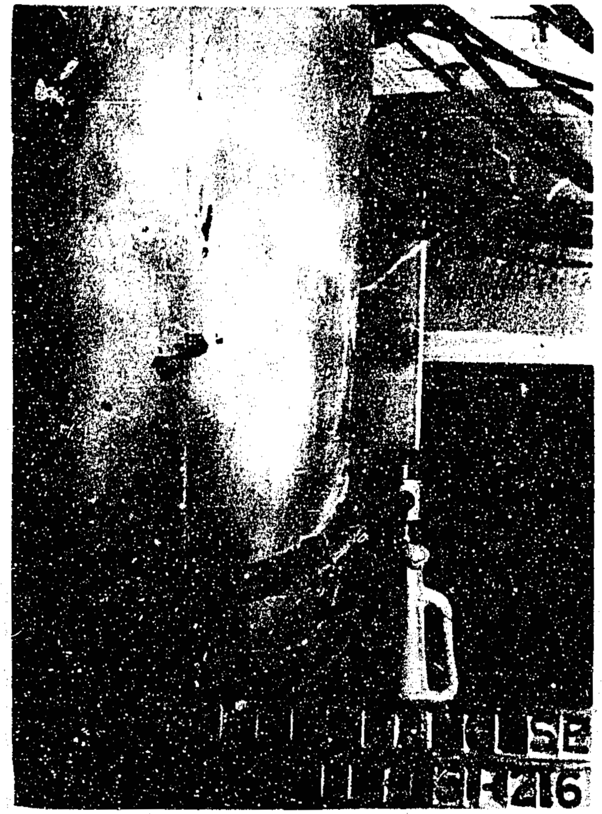
(d) Gate seated--50,000 second-feet.

HUNGRY HORSE DAM SPILLWAY
Flow Entering Recommended Morning-Glory with Proposed
Crest Pier and Guide Vane
1:36 Model

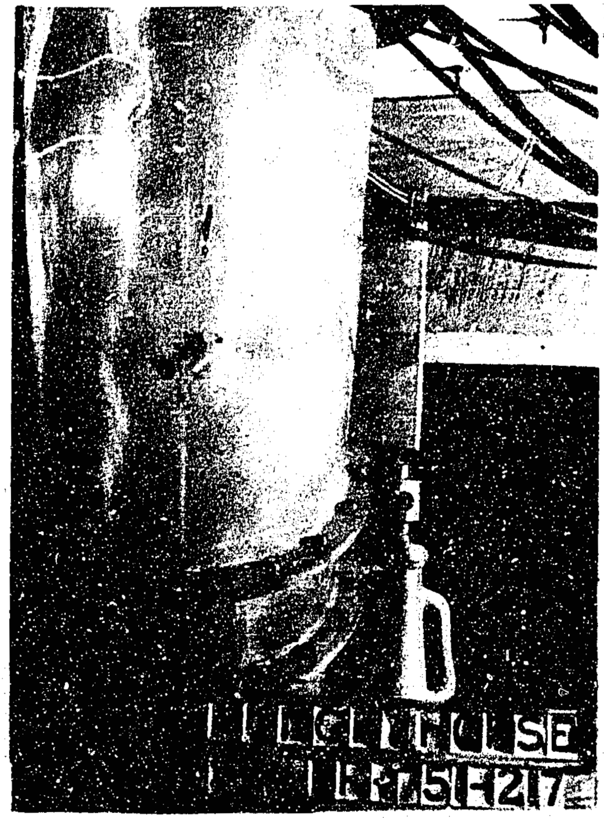
Figure 55
Report Hyd 355



Res. El 3560--Gate elevated--
15,000 second-feet.



Gate seated--35,000 second-feet.



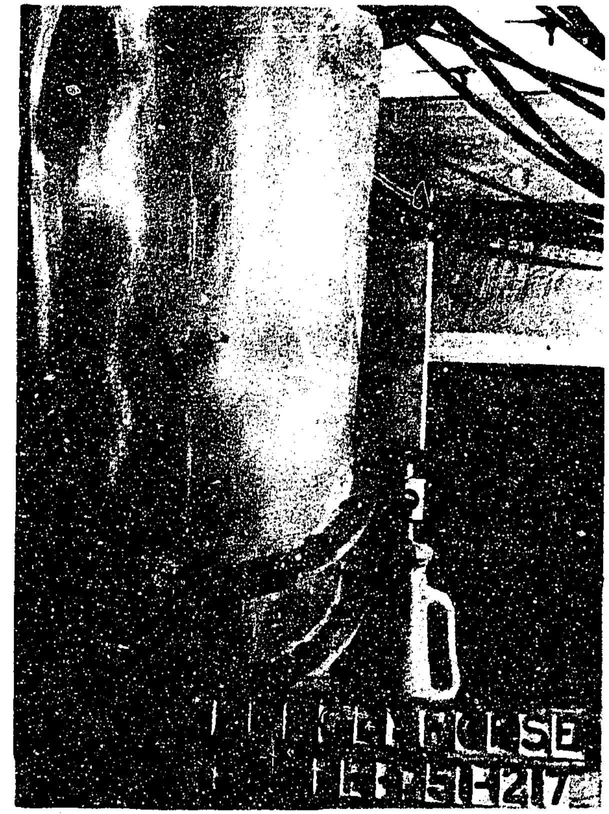
Gate seated--50,000 second-feet.

Note the reduced swirl. Compare with Figure 46.

HUNGRY HORSE DAM SPILLWAY
Flow Through the Upper Bend--Recommended Morning-Glory with
Proposed Crest Pier and Guide Vane
1:36 Model

Res. El 3560--Gate elevated--
15,000 second-feet.

Gate seated--35,000 second-feet.



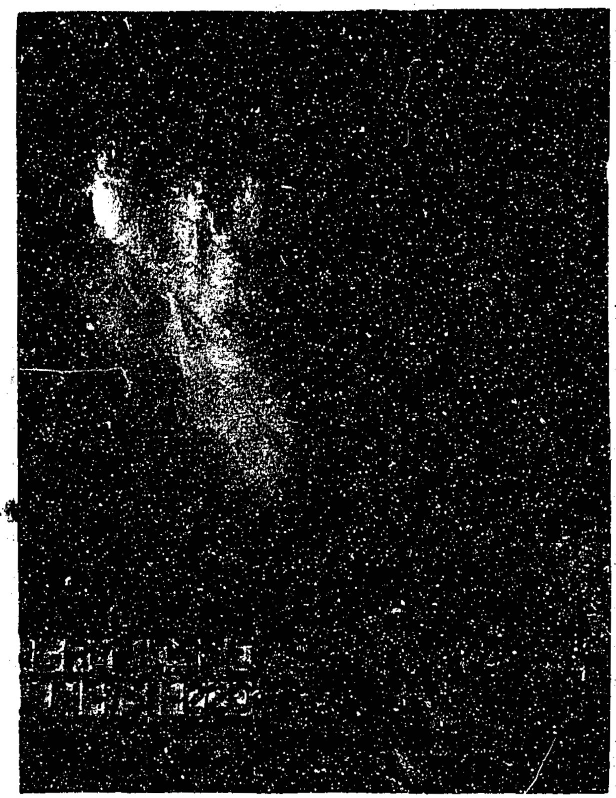
Gate seated--50,000 second-feet.

Note the reduced swirl. Compare **Figure 47**.

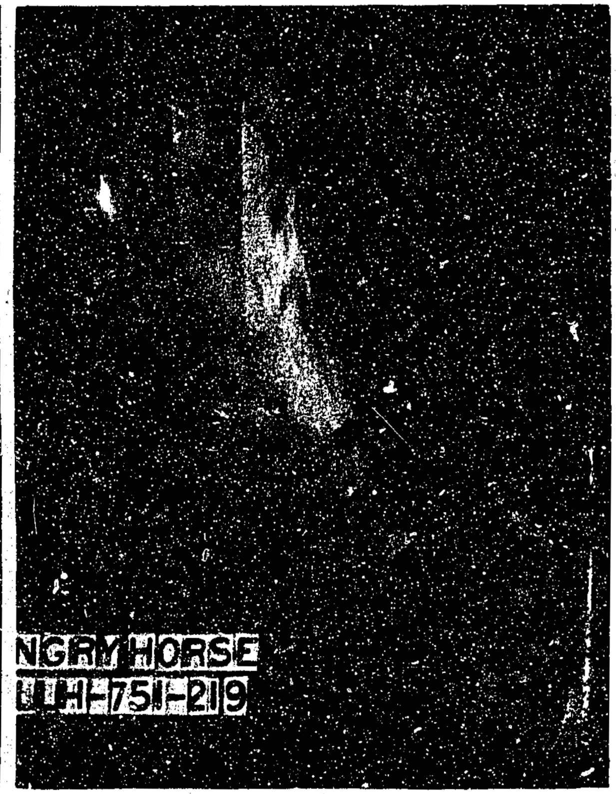
HUNGRY HORSE DAM SPILLWAY
Flow Through the Upper Bend--Recommended Morning-Glory with
Proposed Crest Pier and Guide Vane
1:36 Model

Sheet 1 of 2

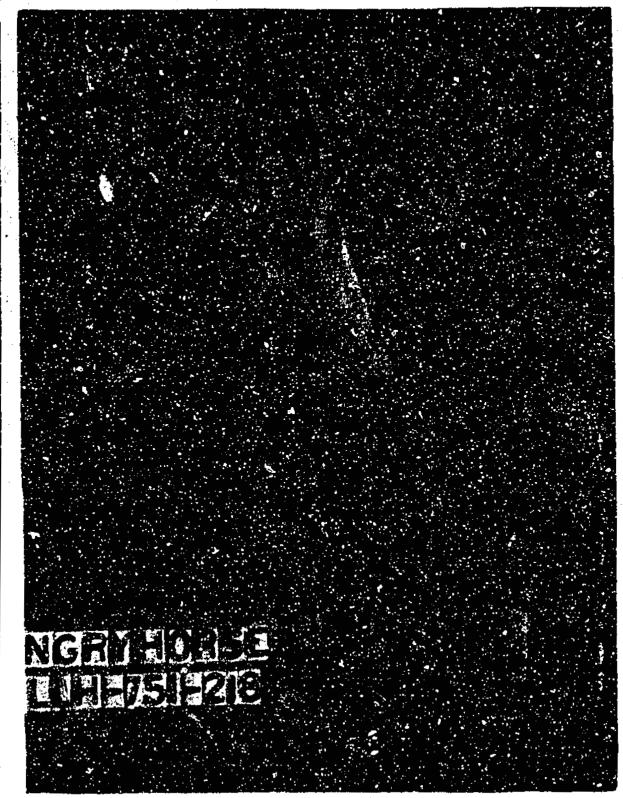
Figure 56(a)
Report Hyd 355



Res. El 3560--Gate elevated--
15,000 second-feet



Gate seated--35,000 second-feet.

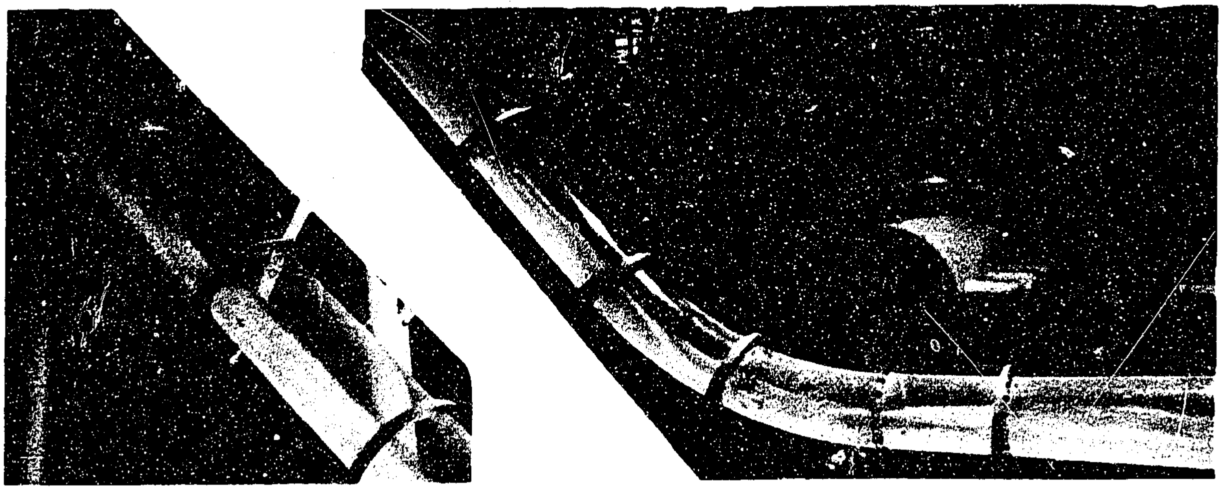


Gate seated--50,000 second-feet.

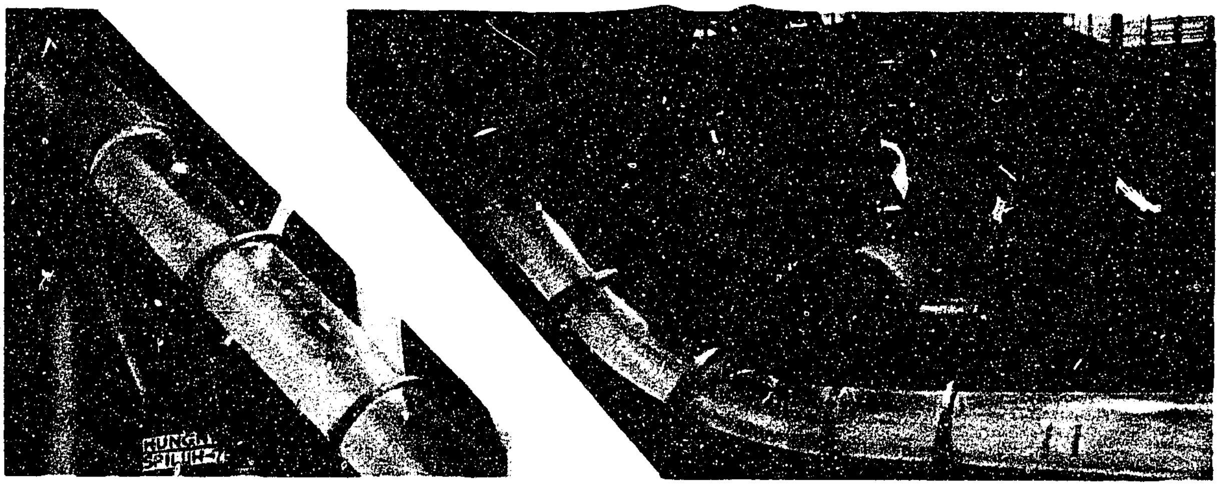
Note reduction in spinning flow. Compare with **Figure 47**. Sheet 2 of 2

HUNGRY HORSE DAM SPILLWAY
Flow Through the Upper Bend--Recommended Morning-Glory with Proposed
Crest Pier and Guide Vane
1:36 Model

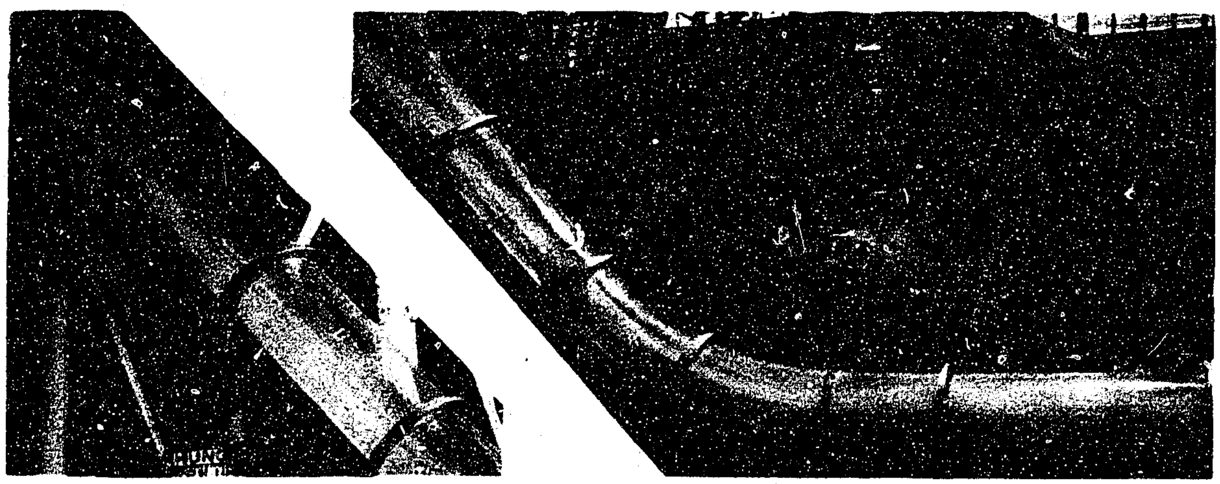
Figure 56(b)
Report Hyd 355



(a) Res. El 3560--Gate elevated--15,000 second-feet.



(b) Gate seated--35,000 second-feet.

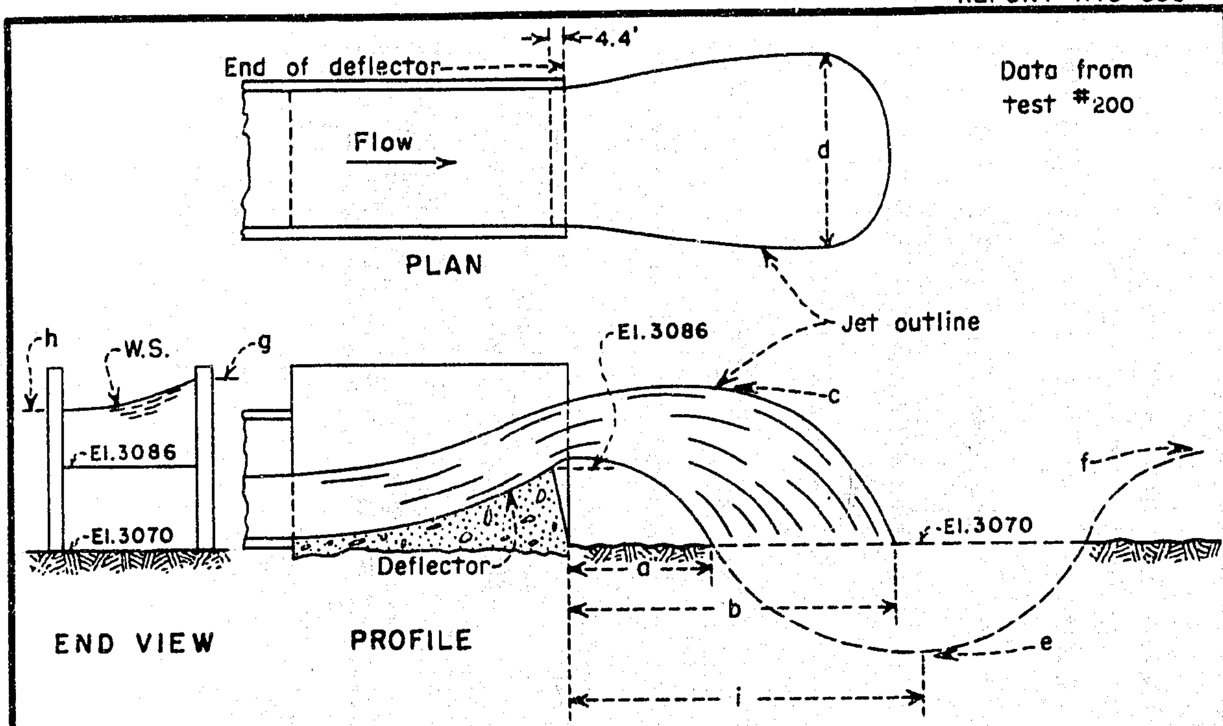


(c) Gate seated--50,000 second-feet.

Note flow is fairly straight for all discharges. Compare with Figure 48.

HUNGRY HORSE DAM SPILLWAY
Flow Through the Tunnel--Recommended Morning-Glory
with Proposed Crest Pier and Guide Vane
1:36 Model

Sheet 3 of 3



NOTE
Scour occurred as a result of a 30 minute model erosion test
All dimensions are in feet.

a. Minimum length of jet projection
b. Maximum length of jet projection
c. Elevation at top of jet
d. Spread of jet
e. Elevation of maximum scour depth
f. Elevation of scour deposit
g. Elevation of water surface at end of deflector on left side
h. Elevation of water surface at end of deflector on right side
i Horizontal distance to point of maximum scour

Q (cfs)	a	b	c	d	e	f	g	h	i
10,000	75.6	223.2	3098.1	60.0	3049	3081	3096.6	3092.75	290
20,000	126.0	316.8	3104.85	64.5	3037	3085	3100.2	3095.36	360
35,000	162.0	367.2	3110.1	66.75	3031	3086	3101.1	3097.1	420
50,000	183.6	417.6	3113.1	66.0	3025	3087	3103.2	3101.0	480

HUNGRY HORSE DAM SPILLWAY
SPILLWAY JET AND EROSION MEASUREMENTS
1:36 MODEL

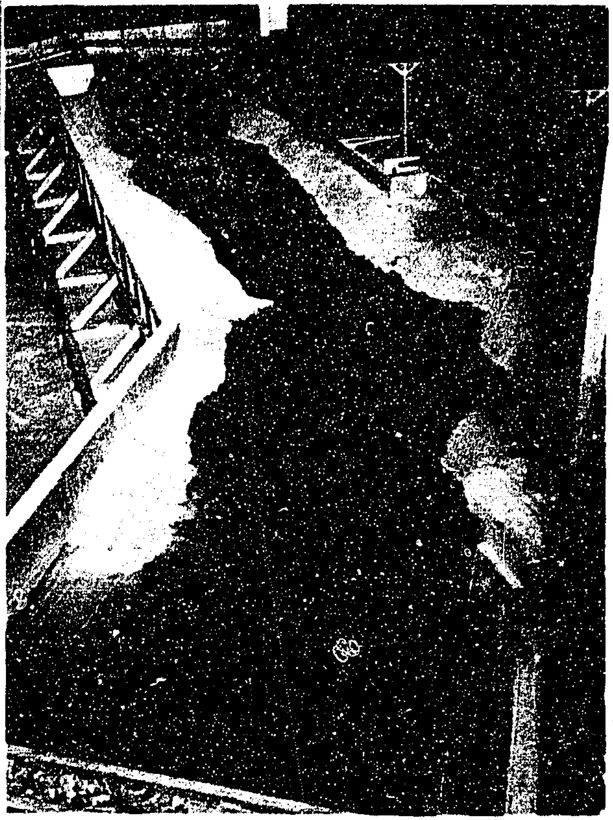
(a) Before test looking upstream.

(d) Erosion after 4 consecutive 30-minute model test runs of 10,000, 20,000, 35,000, and 50,000 second-feet.

(b) Test in progress--50,000 second-feet. Note clearance of jet above channel bed.

(c) Test in progress--50,000 second-feet. Note dry channel upstream.

HUNGRY HORSE DAM SPILLWAY
Erosion in River Channel
1:36 Model



Power Plant--11, 000 second-feet.

Power Plant--11, 000 second-feet.
Outlets--15, 000 second-feet.

Power Plant--11, 000 second-feet.
Outlets--15, 000 second-feet.
Spillway--35, 000 second-feet.

Figure 60(a)
Report Hyd 355

HUNGRY HORSE DAM SPILLWAY
Flow Characteristics in River Channel
1:36 Model

Sheet 1 of 2

Power Plant--11,000 second-feet.
Spillway--10,000 second-feet.

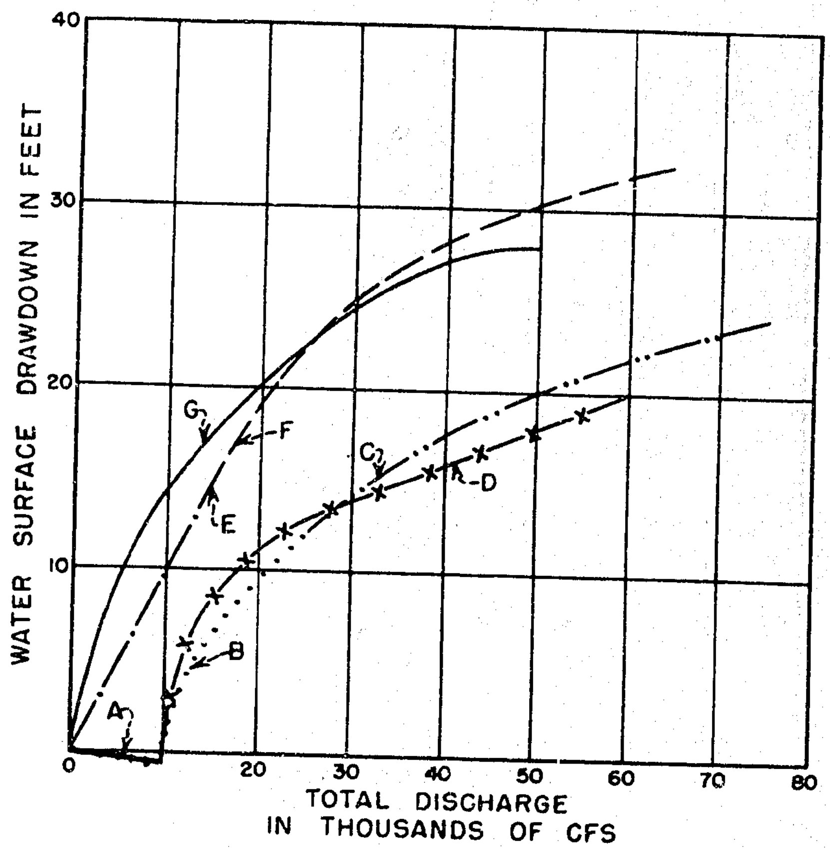
Power Plant--11,000 second-feet.
Spillway--15,000 second-feet.

Power Plant--11,000 second-feet.
Spillway--50,000 second-feet.

HUNGPY HORSE DAM SPILLWAY
Flow Characteristics in River Channel
1:36 Model

Sheet 2 of 2.

Figure 60(b)
Report Hyd 355



SYMBOLS

Data from test #208

A — Powerhouse only discharging

B — Powerhouse discharging 10,000 cfs. plus outlets discharging

C — Powerhouse discharging 10,000 cfs. plus outlets discharging 15,000 cfs. plus spillway discharging

D — Powerhouse discharging 10,000 cfs. plus spillway discharging

E — Outlets only discharging

F — Outlets discharging 15,000 cfs. plus spillway discharging

G — Spillway only discharging

NOTE

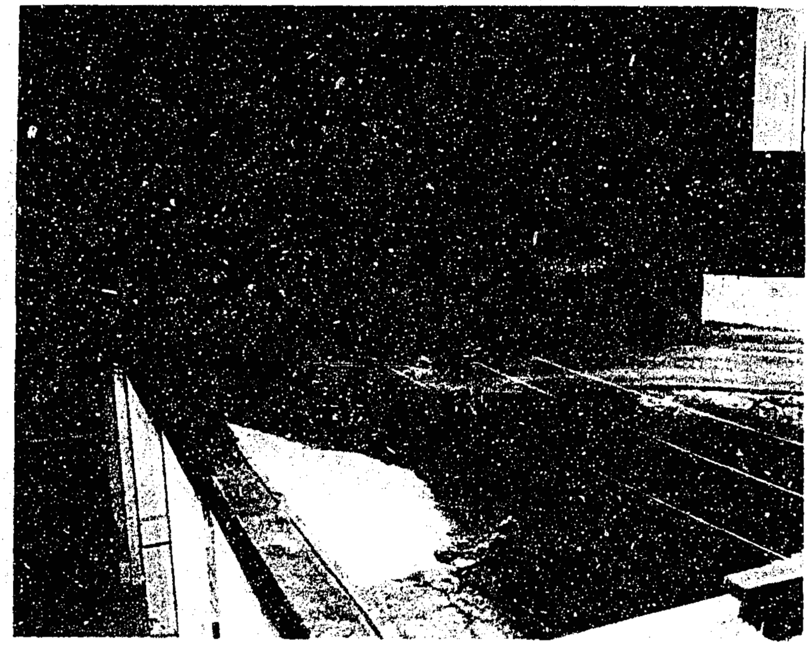
Water surface drawdown is defined here as the difference in elevation of the low tailwater downstream from the powerhouse and the higher tailwater downstream from the spillway jet. The tailwater downstream from the jet was regulated by the tailwater control gate in accordance with the tailwater curve in Figure 3. The two tailwater elevations were measured at the staff gages shown in Figure 10.

HUNGRY HORSE DAM SPILLWAY

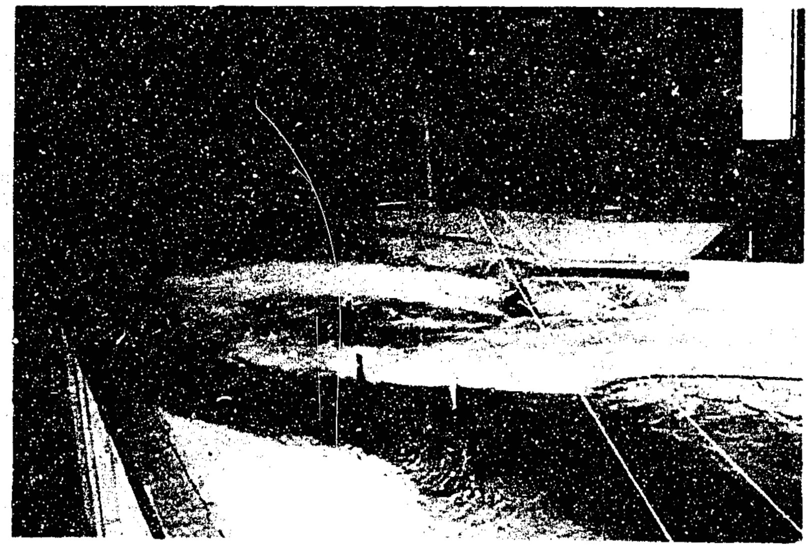
WATER SURFACE DRAWDOWN IN RIVER CHANNEL DOWNSTREAM FROM POWERHOUSE

1:36 MODEL

FIGURE 61
REPORT HYD. 355



(a) Preliminary location.



(b) Recommended location.

HUNGRY HORSE DAM SPILLWAY
Transmission Lines from Powerhouse to Transmission Towers--
Spillway, Outlets, and Power Plant Discharging
1:36 Model